Experimental Investigation of Process Parameters in Electrochemical Machining

A thesis Submitted in partial fulfilment of the requirements for the award of the degree of

Master of Technology
In
Mechanical Engineering
(Production Engineering)
By

Neelam Kumar Verma

Under The Guidance of

Prof. K. P. Maity

Department of Mechanical Engineering
National Institute of Technology Rourkela
Orissa -769008, India

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CERTIFICATE

This is to certify that the thesis entitled — **Experimental Investigation of Process Parameters in Electrochemical Machining** submitted to the National Institute of Technology, Rourkela (Deemed University) by **Neelam Kumar Verma Roll No. 211ME2355** for the award of the Degree of **Master of Technology** in Mechanical Engineering with specialization in**—Production Engineering** is a record of bonafide research work carried out by him under my supervision and guidance. The results presented in this thesis has not been, to the best of my knowledge, submitted to any other University or Institute for the award of any degree or diploma. The thesis, in my opinion, has reached the standards fulfilling the requirement for theaward of the degree of Master of technology in accordance with regulations of the Institute.

Place: Rourkela

Date

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Date   Neelam Kumar Verma

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Abstract

Electrochemical machining is a non-conventional machining process worked with a principle of Faraday's law. It is one of the best alternatives for producing complex shapes in advanced materials used in aircraft and aerospace industries. However, the reduction of the stray material removal continues to be a major challenge for industries in addressing accuracy and improvement. It is very difficult to appliance a high strength, heat-resistant material into complex shapes by conservative techniques, but such materials can be effectively machined by electrochemical machining (ECM) method. This experiment highlights features of the development of a comprehensive mathematical model for correlating the interactive and higher-order influences of various machining parameters on the dominant machining criteria, i.e. the metal removal rate and the surface roughness phenomena, through Taguchi method and RSM method using the pertinent experimental data as obtained by experiment. This experiment also highlights the various test results that also confirm the validity and creativeness of the developed mathematical models for analyzing the effects of various process parameters on the machining rate and surface roughness phenomena. ECM is an electrochemical procedure in which the work piece acts as an Anode and the tool acts as a Cathode. ECM is the controlled removal of metal by anodic dissolution in an electrolytic cell in which the workpiece is the anode and the tool is cathode. The electrolyte is pumped through the gap between the tool and the workpiece, while direct current is passed through the cell, to dissolve metal from the workpiece. Keeping this in view, the present work has been carried out to find out the material removal rate by electrochemical dissolution of an anodically polarized work piece with a copper electrode. In the experiment mild steel and stainless steel (AISI 202) is used as specimen. Experiments were carried out to study the influence of machining parameters such as feed rate, applied voltage, concentration of electrolyte. The results of experiment show the material removal rate increases with increasing voltage, molar concentration of electrolyte, and reduced initial gap. Feed rate is the most important factor in which MRR mostly depends.

Keywords: Electrolyte; Electrochemical machining (ECM); Metal removal rate (MRR); Response Surface Methodology (RSM); surface roughness; Taguchi method.

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Chapter 1

Introduction

1.1 Overview of ECM Process:

ECM is the one of the non-conventional machining process used for machining high-strength, heat resistant, extremely hard materials into complex shapes. ECM is a process based on the controlled anodic dissolution process of the work piece as anode, with the tool as cathode in an electrolytic solution. Its industrial applications have been extended to electrochemical drilling, grinding, deburring and polishing [1]. An electrolytic cell is created in an electrolyte medium, with the tool as the cathode and the work piece as the anode. A high-amperage, low-voltage current is used to dissolve the metal and to remove it from the work piece, which must be electrically conductive. ECM is essentially a depleting process that utilizes the principles of electrolysis. The ECM tool is positioned very close to the work piece and a low voltage, high amperage DC current is passed between the two via an electrolyte. Material is removed from the work piece and the flowing electrolyte solution washes the ions away. These ions form metal hydroxides which are removed from the electrolyte solution by centrifugal separation. Both the electrolyte and the metal sludge are then recycled [2]. ECM was found particularly advantageous for high-strength alloys. For example, the semi-conductor industry frequently requires the machining of components of complex shape and high-strength alloys hence ECM is a major process candidate for semiconductor devices and thin metallic films [3–5]. ECM processes were also adopted in the aerospace and electronics industries for shaping and finishing operations of a variety of parts of the opening windows that are a few microns in diameter [6]. Basic schematic diagram and inter electrode gap is shown in Fig. 1.1 and Fig. 1.2

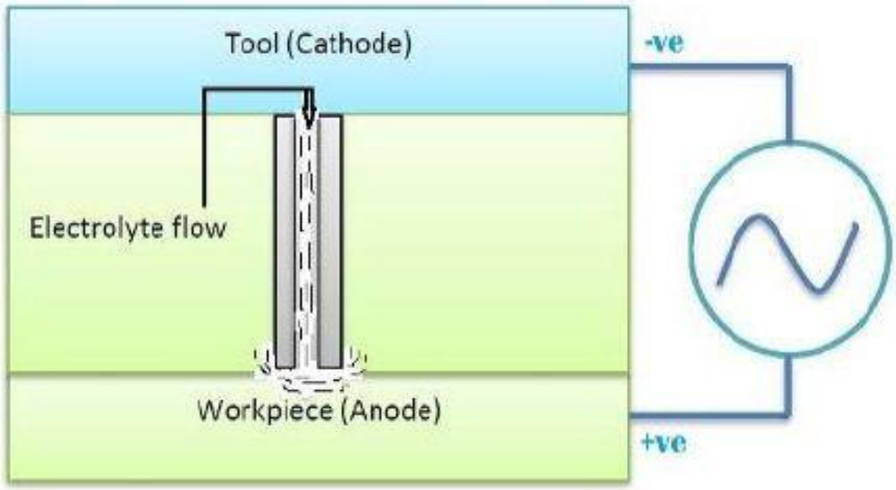


Fig. 1.1: Basic schematic diagram of The ECM process

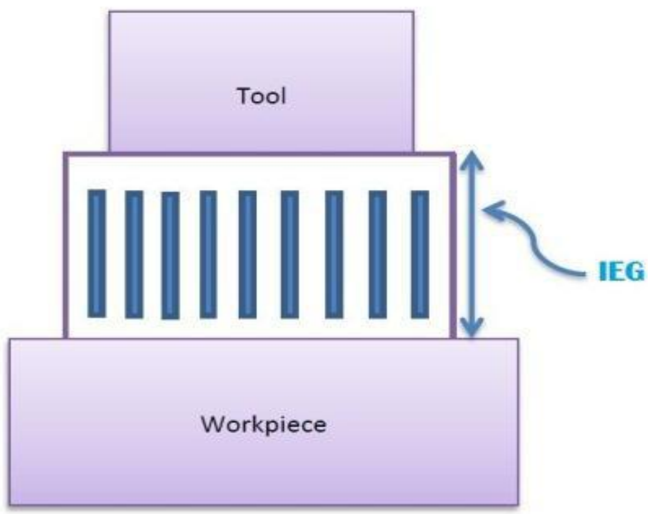


Fig. 1.2: The Inter Electrode Gap or IEG

ECM is a good and effective method in machining of complex shapes. The metal is removed by the controlled anodic dissolution of the anode according to the well-known Faradays law of electrolysis. A Muttamara et. al, presented relationship between ECM parameter and groove depth and groove ratio using Taguchi method [7]. Jagannath Munda et al. investigated the electrochemical micromachining through response surface methodology approach by taking MRR and ROC as separate objective measures, developed mathematical models and analyzed with reference to machining parameters [8].

1.2 Working principle of ECM

Electrochemical machining is based on the electrolysis process. The process is started in the presence of an electrolyte flow that is circulated with the help of special pump filling the inter electrode gap between anode (job) and cathode (tool). Electrolysis principle is in use long for electroplating where the objective is to deposit metal on the work piece. But since in electrochemical machining the objective is to remove the metal, the work piece is connected to the positive terminal and the tool to the negative terminal. The metal is removed by the controlled dissolution of the anode according to the well-known Faradays law of electrolysis. Generally a neutral salt solution of sodium chloride (NaCl) is taken as the electrolyte. The principal and process detailing of ECM for steel is shown in Fig. 1.3

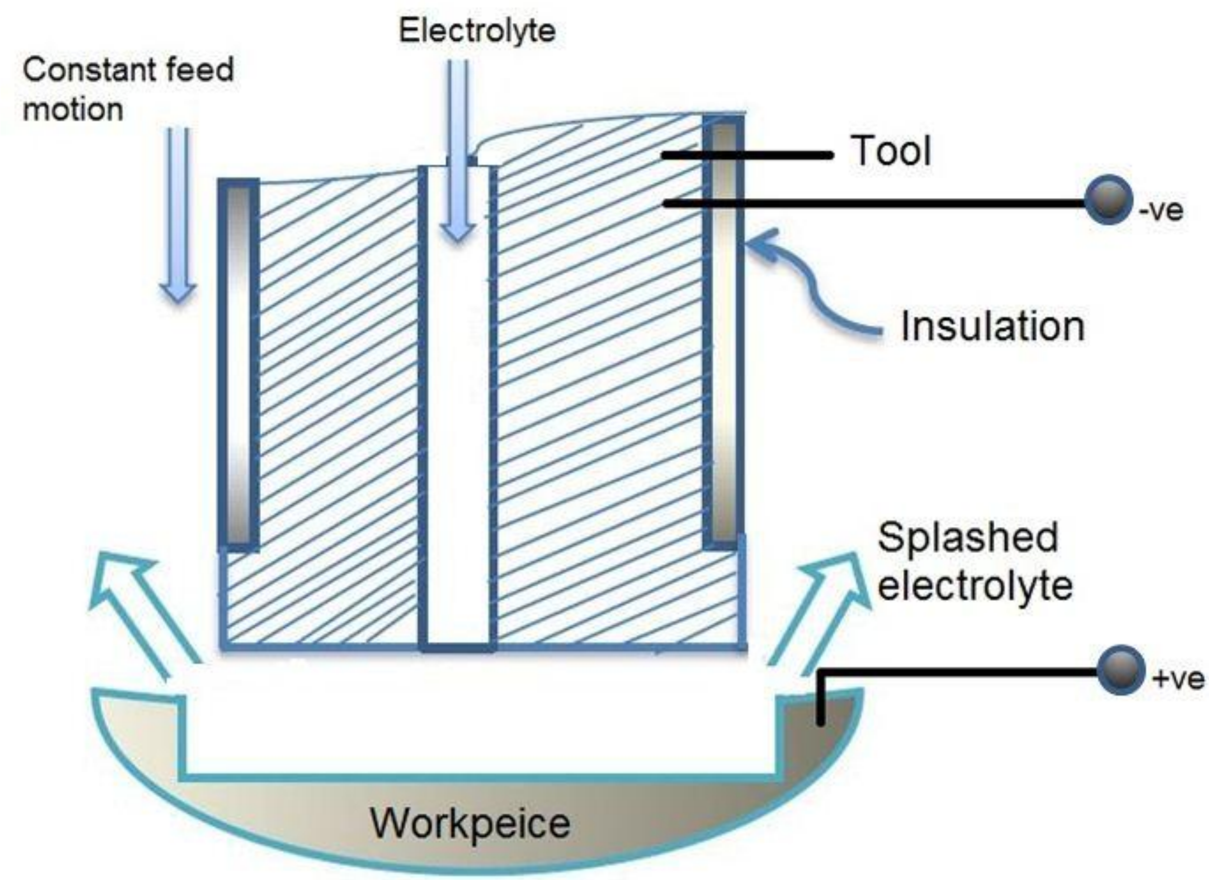


Fig.1.3: Principle of Electrochemical Machining

ECM is widely used in machining of jobs involving intricate shapes and to machine very hard or tough materials those are difficult or impossible to machine by conventional machining. ECM is also most suitable for manufacturing various types of dies and moulds.

1.3 Steps to proceeds ECM process:

During ECM reactions takes place at the electrodes i.e. at the anode or work piece and at the cathode or the tool along with within the electrolyte. Let us take an example of machining of low carbon steel which is primarily a ferrous alloy generally comprising iron. For electrochemical machining of steel, usually a neutral salt solution of sodium chloride (NaCl) is taken as the electrolyte. The electrolyte and water undergoes ionic dissociation as shown below as potential difference is applied.

$NaCl \leftrightarrow Na^+ + Cl^-$
$H_2O \leftrightarrow H^+ + OH^-$

When the potential difference is applied between the work piece (anode) and the tool (cathode), the positive ions move in the direction of the tool and negative ions moves in the direction of the work piece. Thus the hydrogen ions will take away electrons from the cathode (tool) and from hydrogen gas as:

$2H^+ + 2e^- = H_2 \uparrow$ at cathode
in the same way the iron atoms will came out from the anode (work piece) as:
$Fe = Fe^{2+} + 2e^-$
Inside the electrolyte iron ions would combine with chloride ions to form iron chloride
and similarly sodium ions would combine with hydroxyl ions to form sodium hydroxide.
$Na^+ + OH^- = NaOH$

In preparation $FeCl_2$ and Fe $(OH)_2$ would form and become precipitated in the form of slurry. In this manner it can be noted that the work piece gets gradually machined and gets precipitated as the slurry. Besides there is no coating on the tool, only hydrogen gas develops at the tool or cathode. Fig. 1.4 depicts the electro-chemical reactions schematically. As the material removal takes place due to atomic level division, the machined surface is of excellent surface finish and stress free.

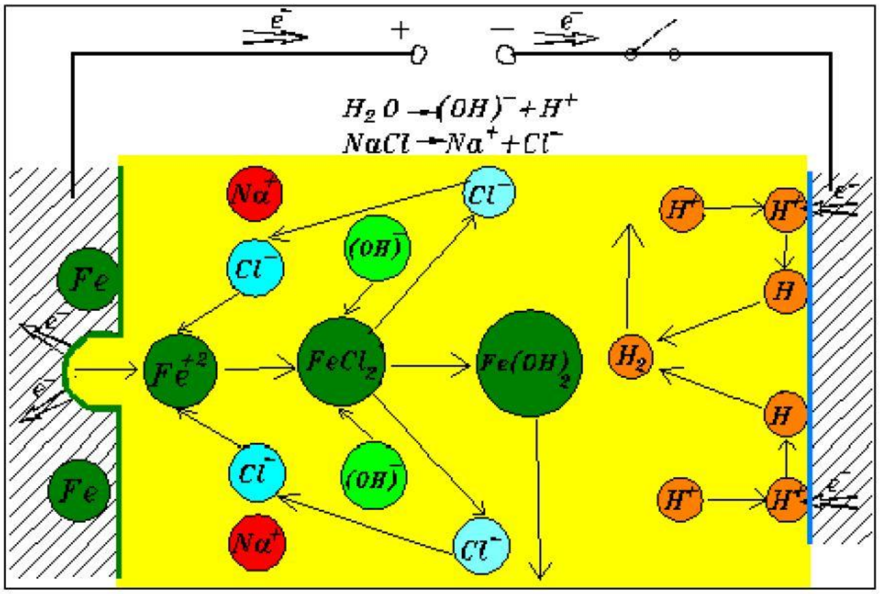


Fig1.4: Electrochemical reactions during ECM of iron in sodium chloride (NaCl) Electrolyte

Reaction at the anode is shown in Figure 1.2 is demonstrated as follows,

$$Fe \leftrightarrow Fe^{2+} + 2e^-$$

$$Fe^{2+} + 2Cl \leftrightarrow FeCl_2$$

$$Fe^{2+} + 2OH^- \leftrightarrow Fe\,(OH)_2$$

$$Fecl_2 + 2OH^- \leftrightarrow Fe\,(OH)_2 + 2Cl^-$$

$$2Cl^- \leftrightarrow Cl_2 \uparrow + 2e^-$$

$$2Fecl_2 + Cl_2 \leftrightarrow 2Fecl_3 \downarrow$$

$$H^+ + Cl^- \leftrightarrow HCl$$

$$2Fe\,(OH)_2 + H_2 + O_2 \leftrightarrow 2Fe\,(OH)_3 \downarrow$$

$$Fe\,(OH)_3 + 3HCl \leftrightarrow Fecl_3$$

$$Fecl_3 + 3NaOH \leftrightarrow Fe\,(OH)_3 \downarrow + 3\,NaCl$$

Reaction at the cathode is given below,

$$Na^+ + e^- \leftrightarrow Na$$

$$Na + H_20 \leftrightarrow NaOH + H^+ \uparrow$$

$$2H^+ + 2e^- \leftrightarrow H_2\uparrow$$

It indicates that lone hydrogen gas will evolve at cathode and there will be no deposition.

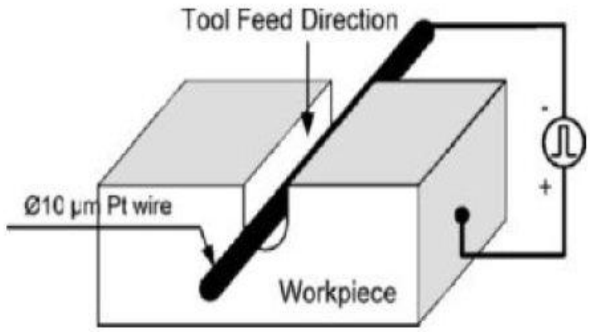
1.4 Classification of ECM process

1.4.1 Electrochemical Turning Process:

ECT is a special application of ECM. The principles of ECM are applied in the process to electrolytically machine rotating work-piece. Peripheral cuts and face cuts are accomplished as illustrated in figure 2.ECT is distinguished from a related process, electromechanical machining (EMM), in the ECT employs a non-contacting tool and all metal removal is accomplished via electrolytic action. In contrast, EMM is a traditional machining process in every way except that electrolyte is flooded over the work-piece surface to soften it prior to mechanical metal removal by traditional tools. Application Large disk forgings are machined using ECT. In some cases, full-face electrodes are plunged into a rotating disk. Bearing races have been finished, with close tolerances and with surface roughness held to less than 5 μ in.(0.13 μ m)Ra. Another application, AISI316 stainless steel work-piece (2.5" ,6.35 mm dia) are electrochemical turned, using an electrolyte of NaCl and $NaNO_3$ (2:3), to a surface finish of less than 10 μ in.(0.25 μ m) Ra with out-of-roundness of less than 0.0002" (0.005 mm) TIR. Operating parameters Material removal rates and tolerances are similar to those achieved in ECM. Tolerance holding capability usually is between ±0.0015-0.003" (0.038-0.08 mm). Under unusual conditions, tolerances can be held to ±0.001" (0.03mm); and in rate cases, tolerances can beheld to ±0.0005" (0.013 mm).

1.4.2 Electrochemical Wire Cutting:

Electrochemical wire cutting procedure for removal of metal uses a wire tool as cathode and work piece as anode. The work piece can be designed by relative movement stuck between it and the wire. The method is like to wire discharge machining. This method is found to be best suitable for cutting in one or two direction and fine drilling. Rectangular wire seems to be better choice over circular section wire. This method has a restricted feed rate compared with conventional ECM. The feed rate is dependent on the width of wire and the diameter of work piece. This procedure is best suited for super finishing with higher surface finish up to 0.15μm. This procedure is very suitable with small work piece dimension. Surface finish is better for flat surface than cylindrical. The power ingestion is low and tooling system is cheap. The material removal rate can be controlled accurately. The surface finish is affected by parameters like feed rate, work-piece relation speed and electrolyte flow rate.



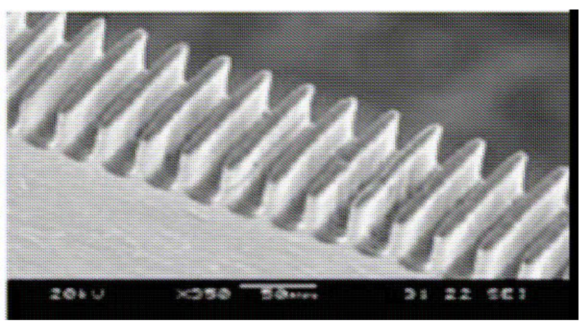


Fig.1.5 Scheme of wire-ECM, (b) Micro-grooves by wire-ECM

1.4.3 Electrochemical Grinding Process:

Electrochemical Grinding, or ECG, is a variation of ECM (Electrochemical Machining) that combines electrolytic activity with the physical removal of material by means of charged grinding wheels. Electrochemical Grinding (ECG) can produce burr free and stress free parts without heat or other metallurgical damage caused by mechanical grinding, eliminating the need for secondary machining operations. Like ECM, Electrochemical Grinding (ECG) generates little or no heat that can distort delicate components.

Electrochemical Grinding (ECG) can process any conductive material that is electrochemically reactive. The most common reason customers choose electrochemical grinding (ECG) is for the burr free quality of the cut. If a part is difficult or costly to deburr, then electrochemical grinding (ECG) is the best option. Materials that are difficult to machine by conventional methods, that work harden easily or are subject to heat damage are also good candidates for the stress free and no heat characteristics of electrochemical grinding (ECG). The stress free cutting capabilities of the process also make it ideal for thin wall and delicate parts. The real value of Electrochemical Grinding (ECG) is in metalworking applications that are too difficult or time-consuming for traditional mechanical methods (milling, turning, grinding, deburring etc.). It is also effective when compared to non-traditional machining processes such as wire and sinker EDM. Electrochemical grinding (ECG) is almost always more cost effective than EDM. The tolerances that can be achieved using ELECTROCHEMICAL GRINDING (ECG) depend greatly on the material being cut, the size and depth of cut and ECG parameters being used. On small cuts, tolerances of .0002" (.005mm) can be achieved with careful control of the grinding parameters.

1.4.4 Electrochemical Drilling Process:

Electrochemical drilling (ECD) is a useful technique for processing small holes on many hard-to-machine metals, and is also a good choice for simultaneous drilling of multiple holes. The electrolyte flow pattern of ECD process could be classified into two types–forward flow and reverse flow. During the ECD process with forward flow, the electrolyte spreads out radially from the centre hole of the electrode in rapid divergence and expansion which cause flow field disrupting phenomena such as cavitation and striation. The disrupting phenomena would worsen the stability of the machining process. The most typical way to minimize flow field disrupting is to apply the reverse electrolyte flow, in which electrolyte crossing from the inter-electrode gap was extruded out from the inlet of the electrode tube to the electrolyte tank under the pump force. But fine dynamic sealing in traditional reverse flow to form an enclosed space in the electrolyte cell is difficult and complicated especially for multiple electrodes. In this research, the reverse flow is achieved in the way of electrolyte-extraction without dynamic sealing. The electrolyte supplied to the machining zone needs only to be exposed to the atmospheric air. The feasibility of implementation of the reverse flow was greatly enhanced. In multiple holes machining conditions, the non-uniform of electrolyte supply will cause different machining status for each hole. This would probably lead to short circuit. The flow distribution along the electrode array is determined by the structure of combining manifold, and the main parameters of the manifold are studied and optimized subsequently.

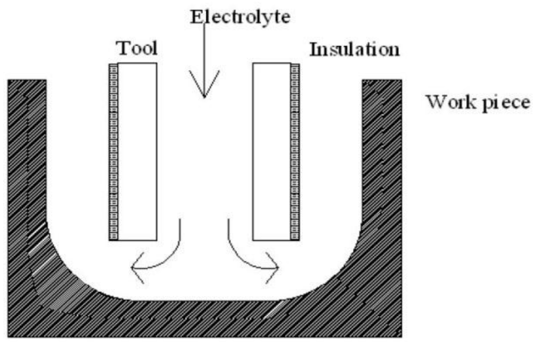


Fig.1.6 Electrochemical drilling process

1.4.5 Electrochemical Honing Process:

It is one of the most potential micro-finishing process in which material is removed by anodic dissolution combined with mechanical abrasion of bonded abrasive grains. The precision finishing of gears by ECH is a productive, high accuracy, long tool life gear finishing process.

Electrochemical honing process can be used to increase the metal removal rate by a factor of 2 or 3 than that achieved in conventional honing. Conventional abrasive honing stones are used to maintain the precise size of the bore. A current density of the order to 15-45 A/cm2 at 6-30v dc is passed to the work piece and electrodes mounted between the stones and fitted with spacers so that there is a gap of about 0.15 mm between the work and the electrode. The electrolyte is supplied under pressure of 5-10 kg/cm2. Conventional and electrolytic metal removal takes place simultaneously. The reciprocating and rotating motion of the tool ensures an accuracy of ±0.002 mm. A surface finish of 0.05µm can be easily achieved in production. The advantages of this process are increased metal removal rate, burr free action, less pressure required between stones and work, reduced noise, and reduced distortion in thin walled components. ECH equipment is available usually for internal honing applications.

1.5 ECM machine Structure:

Electrochemical Machining (ECM) is the controlled removal of metal by anodic dissolution in an electrolytic cell in which the work-piece is the anode and the tool is cathode. The electrolyte is pumped through the gap in between the tool and the work piece, while direct current is passed 10 through the cell, to dissolve metal from the work piece. ECM is extensively applied in machining of jobs involving intricate shapes and to machine very hard or tough materials those are difficult or impossible to machine by conventional machining.

An ECM machine be made up of of a machine structure to locate and provide for the drive of the tool, an electrolyte system and an electric power supply unit. However there are several mandatory characteristics which every machine should express. The characteristics are outlined below:

Steady feed drive: - The feed drive system to the tool should be accurate and steady even at small feed rates. It should not stick-slip under high forces.

Manageable work tank: - The machine operational area should be easily manageable for loading and unloading of work-pieces and also for tool setting. It must be prepared with an attachment to prevent flopping of the electrolyte.

Stiffness: - The machine should possess structural inflexibility to care the work-piece and tooling and repel the hydrostatic and hydrodynamic forces produced by electrolyte pressure.

Power supply: - The main purpose of the power supply is to convert available AC power to DC power by means of rectifiers. Current of the order of 1000-45,000 A is generally required and 5-25 V is applied to overcome the resistance at the gap.

Corrosion resistance: - The machine base, work table and all the applicable constituents should be made of corrosion resistant materials such as stainless steel, fibre glass, plastic, concrete or granite.

1.6 ECM machine parameters:

1.6.1 Servo system:

The servo system controls the tool motion relative to the work-piece to follow the preferred path. It also controls the gap width inside a range that the liberation process can continue. If tool electrode movements is too fast and touches the work piece, short circuit occurs. Short circuit pays little to material removal because the voltage drop between electrodes is lesser and the current is restricted by the generator. If tool electrode moves too slowly, the gap comes to be too wide and electrical discharge never occurs. Another function of servo system is to pull out the tool electrode when worsening of gap state is detected. The width can not be measured during machining; other measurable variables are essential for servo control.

1.6.2 Tool feed rate:

In case of ECM process gap about 0.01 to 0.075 mm is retained between tool and work-piece. For lesser gap, the electrical resistance between the tool and work is minimum and the current is maximum and hence maximum metal is removed. The tool is feed in to the work depending upon the how fast the metal is to be removed. The movement of the tool slide is controlled by a hydraulic cylinder giving certain range of feed rate.

1.6.3 Temperature control:

The temperature of the electrolyte must be constant so that deviation in conductivity will not occur. If the temperature of the electrolyte is low it means lesser rate of metal removal and if it is high, temperature may lead to the vaporization of the electrolyte. Therefore temperature of electrolyte must be maintained between 24° and 60°.

1.6.4 Electrolyte:

The electrolyte is essential for the electrolytic process to work. An electrolyte in ECM performs three basic functions, which are as follows;

(1) Completing the electrical circuit and allowing the large current to pass.

(2) Sustaining the required electrochemical reactions,

(3) Carry away the heat generated and the waste products.

Electrical conductivity of the electrolytes must be high, toxicity and corrosiveness should be low. The electrolyte is pumped at nearby 14 kg/cm^2 and at speed should not be less than 30 m/s.

Table.1.1: Type of electrolytes

SL No.	Alloy	Electrolyte
1	Iron based	Chloride solutions in water (mostly 20% NaCl)
2	Ni based	HCL or mixture of brine and H_2SO_4
3	Ti based	10% hydrofluoric acid + 10% HCL +10% HNO_3
4	Co-Cr-W based	NaCl
5	WC based	Strong alkaline solution

1.6.5 Material removal rate:

Electrolysis is the basis of material removal. Faraday proposed two laws for this, first one is "the amount of chemical change produced by an electric current, which is the amount of any material dissolved or deposited, is proportional to the quantity of electricity passed". Second is "The amount of different constituents dissolved by the equal quantity of electricity are proportional to their chemical equivalent weights". Material removal rate is a function of feed rate which dictates the current passed between the work and the tool. As the tool moves towards workpiece gap decreases and current increases which increases more metal at a rate analogous to tool advance. A steady spacing between tool and work is thus established. It can be noted that high feed rate not only is productive but also produces best quality of surface finish. However feed rate is restricted by removal of hydrogen gas and products of machining. Metal removal rate becomes poor with low voltage, low electrolyte concentration and low temperature. The major advantages of the metal removal rate process are that they do not cause certain unwanted surface effects which arisen in conventional machines. The main benefits are that they are stress free machining, burr free surfaces, reduced tool wear and abolition of thermal damage to the work-piece. These processes have no effect on mechanical properties such as yield strength, ultimate tensile strength, ductility, hardness etc.

1.6.6 Surface finish:

ECM can produce surface finish order of 0.45µm by rotation of tool or work. Any weakness on tool face produce replica on work piece. Tool surface should therefore be polished. The finish is superior in harder material. For optimum surface finish, careful electrode design, maximum feed rate, and surface improving additives in electrolyte are selected. Low voltage decreases the equilibrium machining gap and result in better surface finish and tolerance control. Low electrolyte concentration decreases the machining gap and gives the better surface finish. Low electrolytic temperature also promotes better surface finish.

1.6.7 Tool design:

Since there is no tool wear occur, any good conductor is suitable as a tool material, however it should be designed tough enough to withstand the hydrostatic force, produced by electrolyte being forced at higher speed through the gap in between tool and work. The tool is prepared hollow for drilling holes so that electrolyte should pass along the bore in tool. Some of the problems like stagnation, cavitation and vortex formation in electrolyte flow must be avoided because these result a poor surface finish. It should be given such a shape that the desired shape of job is achieved for the given machining condition. Both external and internal geometries may be machined by an electrochemical machine. Copper is commonly used as the electrode material. Some materials like brass, graphite and copper -tungsten can also be used since they have capability to machined easily and noncorrosive properties.

There are two major features of tool design. Which are as follows:-

1. Defining the tool profile so that the preferred shape of the job is achieved for the certain machining conditions.

2. Designing the tool for concerns other than e.g. electrolyte flow, insulation, power and fixing arrangements.

1.6.8 Filtration and storage tank

Single or multi-stage centrifugal pumps are used on ECM equipment. A least possible flow rate of 15 litre/min per 1000 A. Electrolyzing current is generally required. A pressure of 5-30 kg/cm^2 meets most of the requirements of ECM application

1.6.9 Valves and piping:

The piping and control valves which supply electrolyte to the ECM tooling, must not introduce distant matter into the electrolyte. Stainless steel is the utmost suitable material for valves and piping. Materials such as fibre glass and reinforced plastics are used with some degree of success.

1.6.10 Pumps:

The purification of electrolyte is important to avoid small particles of grit, metal, plastics and products of machining from entering the machining gap and causing interloping in the process. These filters get clogged and cleaning becomes essential once in 30 hrs.

1.7 Features of ECM:

It consists of benefits of ECM, drawbacks and limitations of ECM and application of ECM.

Table 1.2: ECM specification

Tool	Copper, brass, steel
Power supply	Constant voltage 5-30 DC volt
Current	50-40000 Amp
Mechanics of material removal	Electrolysis
Maximum Material removal rate	15000 mm^3/min
Specific power consumption	7 W/ mm^3/min
Electrolyte solution	Neutral salt, brine solution
Accuracy and surface finish	0.02 mm, 0.4 µm
Applications	All conducting metals and alloys
Limitations	High specific energy consumption, not applicable for jobs with very small dimensions, expensive machine
Mechanical properties	Stress free applications, negligible tool wear
Critical parameters	Voltage, current, feed rate, electrolyte
Surface properties	No thermal damage

1.8 Benefits of ECM:

Following are the benefits of ECM process:

1. Machining of hard and brittle material is possible with good quality of surface finish and dimensional accuracy.
2. No mechanical stress impact into the processed work piece.
3. Complex shapes can also be easily machined.
4. The electrolytes generally used mean that the process is seen as environmentally friendly
5. There is almost negligible tool wear so cost of tool making is only one time investment for mass production.

6. There is no application of force, no direct contact between tool and work and no application of heat so there is no scope of mechanical and thermal residual stresses in the work-piece.
7. Very close tolerances can be obtained.
8. No heat-affected zones
9. No burr formation.

1.9 Drawbacks and limitations of ECM:

Following are the drawbacks and limitations of ECM process:-

1. All electricity non-conducting materials cannot be machined.
2. High specific energy consumption.
3. High initial and working cost.
4. Total material and work-piece material should be chemically stable with the electrolyte solution.
5. Designing and making tool is difficult but its life is long so recommended only for mass production.
6. Accurate feed rate of tool is required to be maintained.

1.10 Applications of ECM:

Following are the applications of ECM: -

1. ECM is widely used in machining of jobs involving intricate shapes and to machine very hard or tough materials those are difficult or impossible to machine by conventional machining. It is now routinely used for the machining of aerospace components, critical deburring, Fuel injection system components, ordnance components etc.
2. ECM is also best for manufacturing various types of dies and moulds.
3. ECM is used for making complex shapes of turbine blades.
4. ECM is used for making polishing of gun barrels etc.

Chapter 2

Literature survey

2.1 Overview on Micro ECM:

Masuzawa and Tanshoff [9] discussed about the 3D micro machining by machine tools, the term micromachining refers to the material removal of minor dimensions that range from several microns to several millimetres. Advanced micromachining may consist of various ultra-precision activities to be performed on very small and thin work pieces, small and micro holes, slots and complex surfaces are needed to be produced in large numbers. When those things are performed with conventional machining techniques, the problems one usually encounters are high tool wear rate and heat generation at the tool and work piece interface and subsequent alteration of work piece material characteristics, etc. Rigidity requirements for the tool are another problem in the conventional machining of small and deep holes, complex surface and shapes. In addition, it becomes troublesome to machine three dimensional micro-shapes.

Corbett et al. and Tenigyohi [10, 11] suggested that electrochemical machining (ECM) has seen a resurgence of industrial interest in the last decade due to its various advantages, such as no tool wear, stress free and smooth surfaces of machined product and ability to machine complex shapes in electrically conductive materials, regardless of their physical and chemical properties. Micromachining may literally mean the machining of the dimension between 1 and 999 µm. However as a technical term, it also means that a smaller amount of machining which cannot be achieved directly by conventional techniques.

Dutta, et al. and Osenbruggen et al. [12, 13] This article propose that electrochemical micromachining (EMM) appears to be a promising micromachining technique, since in many areas of application, it offers several special advantages that include higher machining rate, better precision and control, and a wider range of material that can be machined. A better understanding of the high rate anodic dissolution is urgently required for EMM to become a widely employed manufacturing process in the micro manufacturing domain.

Dolbier et al. [14] suggested about the insulation of the electrode that a few methods can coat a micro electrode with a very thin insulation layer. Glass coating is widely used to insulate the side faces of electrodes, but the coating layer is too thick to use for micro electrodes. To reduce coating thickness, additional operation of etching is required. A polymer like parylene has been used for conformal coatings in a wide variety of applications. Insulated tool electrodes have many advantages. They can yield maximum machining rate because the rising time of the double layer potential is minimized. The machining rate of the insulated tool electrode is much higher than that of the uninsulated tool electrode. The machining depth can be increased because there is no size effect according to the machining depth, as shown in Fig. 2.1

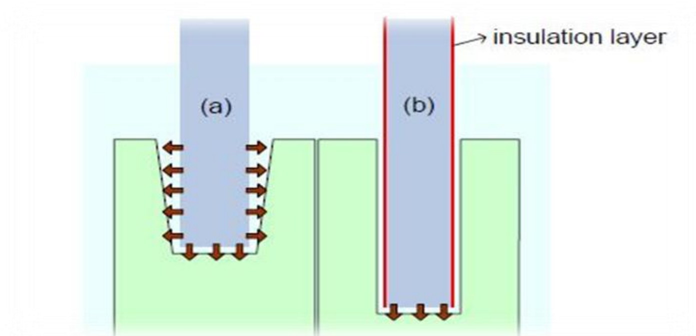


Fig.2.1: Schematic diagram of side effect (a) uninsulated tool, (b) insulated tool.

Bhattacharyya et al. [15] defined that for a better understanding of high rate anodic dissolution processes is urgently required for electrochemical micromachining (EMM) to become a widely employed manufacturing process in the electronic and precision manufacturing industries particularly in the micro manufacturing domain. A successful attempt has been made to develop an EMM setup for carrying out in depth independent research for achieving satisfactory control of electrochemical machining process parameters to meet the micromachining requirements. The developed EMM setup mainly consists of various sub-components and systems, e.g., mechanical machining unit, micro tooling system, electrical power and controlling system and controlled electrolyte flow system, etc. All these system components are integrated in such a way that the developed EMM system setup will be capable of performing basic and fundamental research in the area of EMM fulfilling the requirements of micromachining objectives.

Leea et al. [16] studied the flow channels of a PEM fuel cell are fabricated by the EMM process. The parametric effects of the process are studied by both numerical simulation and experimental tests. For the numerical simulation, the multiphysics model, consisting of electrical field, convection, and diffusion phenomena is applied using COMSOL software. COMSOL software is used to predict the parametric effects of the channel fabrication accuracy such as pulse rate, pulse duty cycle, inter-electrode gap and electrolytic inflow velocity. The experimental fabrication tests showed that a shorter pulse rate and a higher pulse current improved the fabrication accuracy, and is consistent with the numerical simulation results.

Lu et al. [17] In this report the study of micro-proton exchange membrane fuel cell (μ-PEMFC), has been developed significantly as a promising electrochemical power source in portable and miniature electronic devices. species transport and contact resistance determined the performance of the μ-PEMFC. The contact resistance changed significantly the distribution of over potential in the μ-PEMFC and decreased the current output. Small dimensions of the-channel drastically affected the species transport and resulted in a non-uniform current distribution along channel direction at low cell potential (high current). Therefore, the designs of new flow field configurations and assembling modes of μ-PEMFCs are very important in improving the performance of μ -PEMFCs.

Hotoiu et al. [18] this study reveals about the PECCM, Pulsed electrochemical micromachining (PECMM) is a metal shaping process that exploits the double layer's capacitive effect to confine the machining reaction. By applying nano second pulses this effect is strongly enhanced and confines the faradaic current to electrode regions where the tool work piece gap is the smallest. Potential model with time varying boundary conditions is used for the simulation. The double layers are modeled by the capacitor equation in parallel with the Butler-Volmer equation. The temperature in the system is calculated based on the internal energy balance equation, having as natural boundary conditions the heat generated by the electrochemical reactions. The cooling is performed through conduction, having jet specific heat transfer coefficients. For obtaining the mesh deformation according to the electrochemical metal removal, the linear elasticity equations are solved, having the Faraday's law as essential boundary conditions. Numerical simulation of PECMM when every pulse is considered, are computationally extremely expensive. The temperature in the system is not critical but a few degrees increase can significantly influence the electrochemical reactions and hence it is worth being investigated.

Datta and Harris [19] this report tells that whenever ECM machining is applied to the micro-machining range of applications for manufacturing ultraprecision shapes; it is then called electrochemical micro-machining (EMM). EMM appears to be a very promising micro-machining technology due to its advantages, which include high MRR, better precision and control, short machining time, reliability, process flexibility, and environmental acceptability, and it also permits the machining of chemically resistant materials like titanium, copper alloys and stainless steel, which are widely used in biomedical, electronic and MEMS applications. EMM can be advantageously employed in most applications related to the micro-machining of metallic parts due to its cost effectiveness and the high precision achievable; these parts were previously fabricated by chemical micro-machining.

Sen and Shan [20] has reported that electrochemical machining processes provide a viable alternative for drilling macro- and micro-holes with exceptionally smooth surface and reasonably acceptable taper in numerous industrial applications particularly in aerospace, electronics, computer and micro-mechanics industries. Advanced hole-drilling processes like jet electrochemical drilling have found acceptance in producing large number of quality holes in difficult-to-machine materials. This paper highlights the recent developments, new trends and the effect of key factors influencing the quality of the holes produced by these processes. A comparative study of electro jet drilling with another non-traditional hole-drilling process (laser percussion drilling) has been presented which shows the potential and versatility of the electrochemical hole drilling processes.

2.2 Electrochemical Finishing:

Kumar et al. [21] this report tells about the Precision technologies which have stringent demands on micro/nano-surface finishing processes requires hygienic surfaces that are free from lays and stresses induced by finishing processes. This review focuses on fundamental principles and controlling parameters of the ECF/ECP processes that have been developed through cross innovations. It encompasses a detailed classification of the processes followed by their salient features and capabilities. In this process removal occurs because of differential dissolution, where the coupled work piece and tool acts as anode and cathode respectively. Both the electrodes are immersed in an appropriate electrolyte and a high current with a low DC voltage potential difference is normally applied. The electrolyte used in this process is a viscous acid.

Datta et al. [22] have used various compositions of phosphoric acid and sulphuric acid with butyl alcohol, isopropyl alcohol, glycerol as well as chromic ac id for finishing of high-speed print bands. They observed that a mixture of butyl and isopropyl alcohols does not improve the surface finish, while the mixture made with chromic acid causes localized attack and produces highly rough surface. On the other hand, an electrolyte with glycerol gives good surface finish because it influences the physical properties of the electrolyte. It also affects the transport properties of the diffusing species, thereby creating favourable conditions for finishing. Apart from these, it lowers the operating current density.

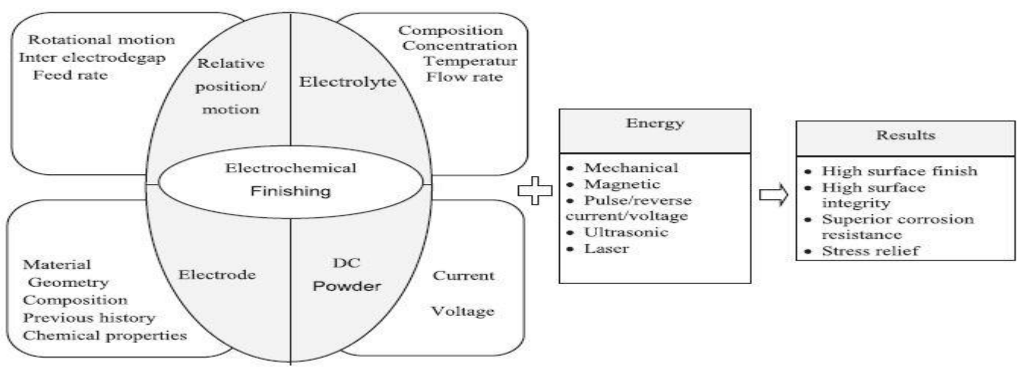


Fig.2.2: Main parameters of electrochemical finishing process

P. S. Pa, [23] suggested that the basic purpose of providing the ultrasonic vibration is to cause effective discharge of electrolyte and by-products in ECF/ECP. Experimental results show that ultrasonic vibrations can give 21–44% improvement in surface finish, depending upon the process variants and conditions used. The use of ultrasonic energy began in 1927 to produce holes in a glass bar. Later on, its application was extended to welding, metallurgy and cleaning processes. Likewise, it has been utilized in electrochemical finishing processes to enhance surface finish.

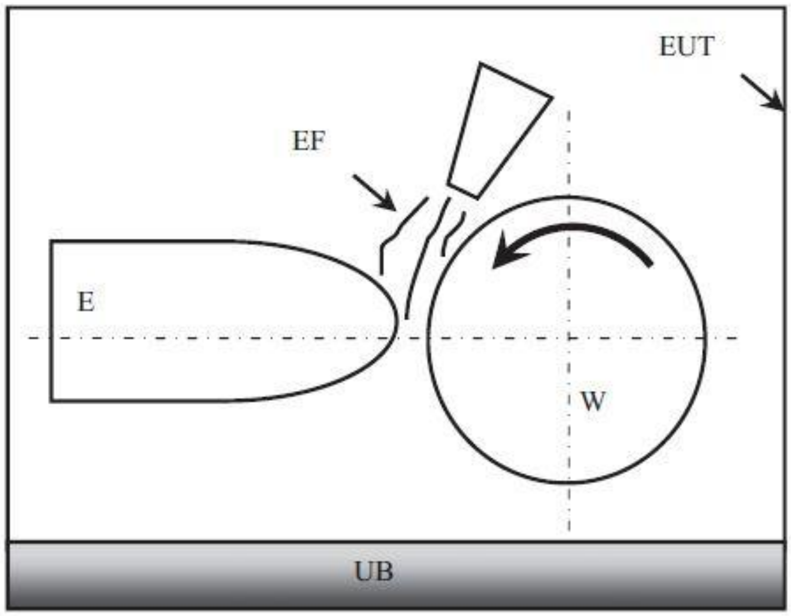


Fig.2.3: Ultrasonic electrochemical finishing process

Where E, electrode (cathode); EF, electrolyte flow; W, work (anode); EUT, electrolytic and ultrasonic tank; UB, ultrasonic base, Feed of cathode perpendicular to page in and out.

2.3 Electrochemical Polishing Process:

Mahdavinejad and Hatami [24] have reported that the electro-chemical machining appears to be inner surface polishing of complex parts with high precision can be easily done by electrochemical polishing method. In this research, cartridge house inner surface electrochemical polishing of a gun pipe, with numerous serial surface angles, is analyzed. So that, according to the various set ups, the optimized polishing parameters are obtained. The comparison between electrochemical polishing and conventional methods from this point of view, shows good advantages of this method, so that, the machining time is more than 30 times less and with very high-surface quality. Besides, the dimensional accuracy of the work piece repeatability process in this polishing method is noticeable.

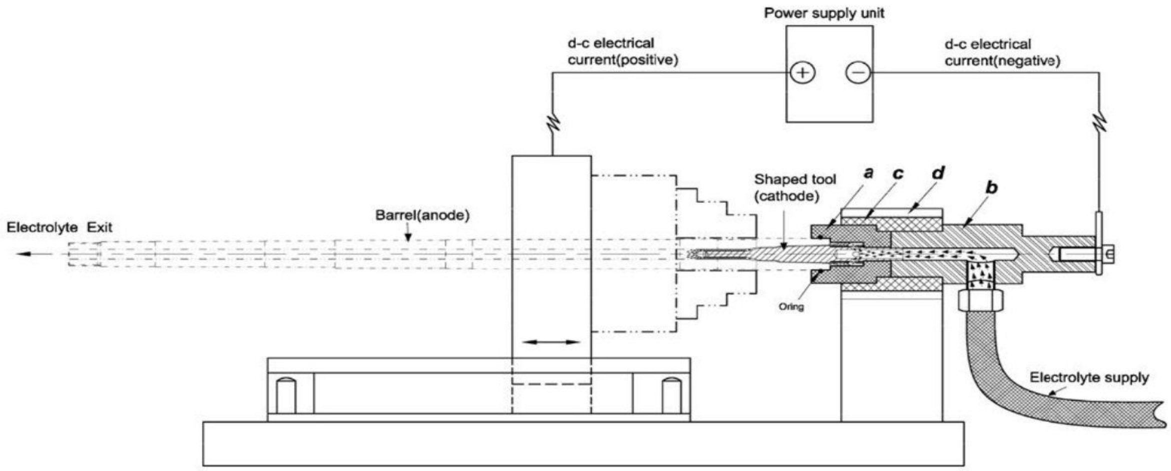


Fig.2.4 Schematic View of Fixture and the circulation of electrolyte

Lee et al. [25] in this paper, the polishing mechanism of the electrochemical mechanical polishing (ECMP) technology for tooling steel SKD11 was investigated. Suitable electrochemical process parameters were evaluated. The electrochemical characteristics of a material such as active, passive and trans-passive (dissolution) can be revealed from its I–V curve. The characteristics of passive and trans-passive have great effects on the ECMP polishing mechanism. Experimental procedures included qualitative, quantitative and surface quality analyses. Qualitative analyses utilized potential state to study the I–V curves of a specific specimen in various electrolytes and electrolytic concentrations, and to find out the voltages at each electrochemical state. In quantitative analyses, the electrochemical polishing processes of the ECMP technology were conducted. From the measured and theoretical weight losses, each process state can be verified whether or not it followed the Faraday's law. Finally, the surface roughness was measured by a surface profiler. The scanning electron microscopy (SEM) was used to observe the surface profile. The energy dispersive spectroscopy (EDS) analysis was employed to analyse the metallurgical compositions of the surface. In summary, the proposed mechanism and analyses were a good methodology in finding suitable electrochemical process parameters for ECMP technology.

Hocheng and Pa [26] has reported that the electro-chemical study, electro-polishing using a turning tool as the electrode for several die materials following turning is investigated. The proposed method uses a traveling electrode instead of the mating electrode as in conventional ECM hence the dimensional error can be controlled more effectively. Further, the method removes a certain limited amount of material, therefore the complex pre-polishing as required in the soakage electro-polishing method is eliminated. This process can be used for various turning operations including end turning, form turning, and flute and thread cutting.

Dobrev et al. [27] studied about the surface improvements after laser milling. ECP is generally applied on macro-scale components, and its application for improving the surface finish of laser milled surfaces poses a considerable challenge. The macro-scale electro-polishing process depends on the uniformity of the material microstructure, the lack of surface inclusions, and the consistency of the surface finish all over the component. The main factors influencing the ECP process feature sizes, especially those of the microstructures together with the applied temperature control, the existence of solution agitation, and the process duration. The ECP process is directed mainly at improving the surface quality. Although ECP displayed some limitations when polishing micro features, it still managed to achieve almost 30% improvement in comparison to the initial roughness after laser milling.

2.4 Electrochemical Turning Process:

Taweel and Gauda (28) integrated the electrochemical turning (ECT) process and magnetic abrasive finishing (MAF) to form a combined process that restores the material removal rate (MRR) and declines surface roughness (SR). A comprehensive mathematical models based on response surface methodology (RSM) for relating the cooperating and higher-order influences of major machining parameters, i.e. magnetic flux density, applied voltage, tool feed rate and work piece rotational speed on MRR and SR of 6061 Al/Al_2O_3 (10% wt) composite. Supporting ECT with MAF is a creative and encouraging process that leads to an increase machining efficiency and resultant surface quality significantly, as compared to that achieved with the traditional ECT of some 147% and 33%, respectively.

P. S. Pa (29) studied a newly designed finishing process employing an effective electrode and a grinding tool to perform the continuous electrochemical finishing and grinding processes followed by turning process. The electrode was tested with both continuous and pulsed direct current. A higher workpiece rotational speed produced a improved finish. Changing the electrode design from a semicircle to a segment form with a small end radius caused the electrolytic products and heat to dissipate more rapidly and provided the best finishing. Pulsed direct current finishing was to some extent better than using continuous direct current finishing. However, the use of pulsed current would increase machining time and cost. The continuous processes of electrochemical finishing and grinding succeeding turning by the design's finishing tool necessitate a lesser time to produce a smooth and bright work piece surface. The design's finishing tool with an effective electrode and a grinding tool provide the optimum value for higher current density, and it provides larger discharge space, thereby producing a smoother surface. The use of a higher electrolytic flow rate and a high work piece rotational speed creates a better finish.

2.5 Electrochemical Grinding Process:

Maksoud and Brooks [30] have informed that the research investigates the process of electrochemical grinding (ECG) used to machine metal-bonded diamond composite wheels. These wheels have been used as form tools to grind ceramics. The wheels must be machined to form and to tight tolerances, in good time. The best methods of the metal-bonded types are those with mild steel and bronze bonds. To machine these wheels using ECG, direct nickelplated diamond composite form tools has been used. In order to achieve the vital tight tolerances and minimum production time, the method has to be optimized. The optimization standard was based on the tolerances of the machined form, on the surface topography of both the metal bond wheel segments (as the work piece) and the plated form tool and correspondingly on the grinding time observed. Operational constraints such as feed rate, electrolyte flow and current density, were investigated. The optimum operating conditions were evaluated. A comparison with conventional grinding methods was made also.

Curtis et al. [31] discussed about design and manufacture concerns are detailed for a hybrid electrochemical grinding unit modified from a vertical machining centre using a 40000 rpm spindle and 500A DC generator. Consequently, experimental work is accessible on the impact of tool bond systems, super abrasive grit type and electrical parameters when simultaneous ECM/grinding Udimet 720 using 10–15 mm diameter plain points. Single layer electroplated CBN tools produced G-ratios and maximum normal cutting forces of 450 and 45 N, respectively, compared to 128 and 557 N for equivalent diamond wheels. Data on work piece unevenness and overcut are also offered as are initial results for a fir tree shaped tool.

Ohmori et al. [32] discussed about the present study, electrolytic in-process dressing grinding was accomplished on surgical steels (type 420J2 stainless steel) and the processing features and resulting surface properties were evaluated. In particular, we used different grinding abrasives to examine the effect of grinding parameters on the surface hydrophilicity of the processed work pieces. The results established that surfaces processed with alumina abrasives in a grinding fluid at temperatures over 50^0C have the highest hydrophilicities. Besides, they also exhibit excellent corrosion resistance.

Komotori et.al [33] in this study, a stainless steel mirror-finished surface achieved by a high precision grinding method was examined in detail using some advanced surface analysing techniques. We establish that the mirror surface grinding technique produced a stable oxide layer on the work piece surface, and also that the abrasive elements of the grinding wheel penetrated and diffused into the substrate. Compared with surfaces that had been polished, surfaces that had been mirror-finished by grinding process exhibited superior surface properties containing hardness, tribological and fatigue properties, corrosion and high temperature oxidation resistances, and adhesive strength with coating films. In addition, varying the processing conditions offers the possibility of adjusting the electrical potential characteristics and hydrophilicity of the surfaces.

Lyubimov et al. [34] has specified that, the peculiarities of synthetic diamond wear in tools for electrochemical grinding are studied for the machining of metal ceramic hard alloys. The impact of structure, mechanical characteristics of both diamond grains and hard alloys as well as the regimes of grinding on diamond wear are considered. Data of diamond ingesting through electrochemical grinding are accessible in comparison with the routine grinding process. Initiation and development and the common relation of numerous components of the diamond deterioration cracking, abrasion, adhesion, diffusion and chemical wear at the electrochemical grinding are discussed. Best regimes of hard alloy electrochemical grinding are suggested: working voltage 5–8 V; current density 20–60 A/cm^2; normal component of grinding force 1.5–2.0 MPa; grinding speed 12–15 m/s.

Zaborski et al. [35] has stated that, there were the procedures of solid bodies wear discussed as well as the types of wear of abrasive tools (cathodes) in abrasive electrochemical grinding (AECG). Group of factors having vital influence on the abrasive tools wear was mentioned. Some mechanisms of the abrasive tools wear were introduced. The linear wear measurements of cathode against the grinding time and volumetric output in mechanical grinding and electrochemical grinding of sintered carbides G20 and Ti alloy WT3-1 were done. The practical conclusions based on the tests performed were included.

2.6 Electrochemical machining of Ti alloys:

Clifton et al. [36] displays characteristics of low density, high stiffness, good creep resistance and high strength at extensive range of temperatures make titanium aluminide a potentially significant material in respect of weight savings in high performance components working at high temperatures. Some work has previously been conceded to inspect properties of the machining of this alloy using mechanical stock removal techniques such as turning. Such approaches are found to have confines in terms of surface integrity blemishes and the formation of surface hardened layer. In this paper the ECM features of titanium aluminide are examined. Conditions under which reproducible ECM is viable for this material has been established and parameterised in terms of machining constraints generated from chronoamperometric analyses for both chloride and per chlorate electrolyte systems.

Aspinwal et al. [37] has stated that titanium intermetallic materials are possible to play a important role in the production of future aero engines. The paper specifies the machinability of a collection of gamma titanium aluminide (y-TiAl) intermetallic alloys when turning, grinding, HSM, drilling, EDM and ECM. Complete literature review data is augmented with experimental results for turning; turn milling and temperature measurement when high speed milling. In spite of the capability to produce crack free surfaces when grinding and HSM, turning and drilling remain problematic. Turned surfaces are in general categorized by work piece spreading, various arc shaped cracks, subsurface lamellae distortion and significant strain hardening, though the use of PCD tooling and ultrasonic aided cutting has been shown to reduce these effects. Application of ECM in micro scheme technologies has to take into account the role of microscopic heterogeneities of steel, e.g. of carbides as established by Haisch et al. [30]. Therefore, the anodic metal dissolution of the alloyed carbon steel 100Cr6 was investigated in NaCl and $NaNO_3$ electrolytes. In flow channel experiments, high current densities up to 80 A/cm^2 and turbulent electrolyte flow velocities has been used. Unsolvable carbide particles cause a deceptive current efficiency >100% in NaCl and >67% in $NaNO_3$. These particles are enhanced at the surface in NaCl solution and perceived by ex situ scanning electron microscopy and energy dispersive X-ray experiments. Auger electron spectroscopy, in mixture with sputter depth profiling, was used to regulate the film composition resulting from the $NaNO_3$ process. This shows the enhancement of carbide particles not however parted from the surrounding steel. Qualitative metal dissolution models on the basis of the investigational effects were proposed for the metal dissolution processes in the NaCl and $NaNO_3$ electrolytes.

Masuzawa et al. [38] has described an experimental study on finishing the surface of tungsten carbide alloy. An exceptional design of the pulse train for alternate polarity ECM is projected for understanding an uniform design dissolution of tungsten carbide and for conquering the dissolution of the tool electrode. The efficiency was confirmed by relating the pulse on an

EDMed surface. A smooth surface lacking heat affected layer or cracks was attained. The experiments also led to hints for selecting the electrode material.

2.7 Objectives of the present work:

The objective of present work is an attempt to finding out the MRR and SR for the mild steel specimen with a Cu electrode by Taguchi and RSM design and MRR, overcut and circularity error was analysed for stainless steel (AISI 202) specimen with RSM design. Overcut and circularity error was analysed by Grey Taguchi coupled with principle component analysis.

Chapter 3

Experimental setup

In this chapter the experimental work was discussed which consists of experimental set up, selection of work piece of material, design of electrode and experimental process. By taking all this information in account material removal rate and surface roughness is calculated.

3.1 Experimental setup:

In this experiment the entire work has been carried out by Electrochemical Machining set up from METATECH-Industry, Pune which is having input Supply of - 415 V+/- 10%, 3φ AC, 50 HZ. Output supply is 0-300 A DC at any voltage from 0-25 V and efficiency is better than 80% at partial and full load condition. The insulation resistance is not less than 10 Mega ohms with 500V DC. And consist of three main sub systems which are being discussed in this chapter. The set up consists of three main sub systems.

1. Machining Cell
2. Control Panel
3. Electrolyte Circulation system

3.1.1 Machining Cell

This electro-mechanical assembly is a robust structure, related with precision machined components, servo motorized vertical up/down movement of tool, an electrolyte providing arrangement, illuminated machining chamber with see through window, job fixing vice, job table lifting mechanism and durable stand. All the exposed components, parts have undergone proper material selection and coating/ plating for corrosion protection.

Technical data

- ✓ Tool area – 122.72 mm^2.
- ✓ Cross head stroke- 150 mm.
- ✓ Tool feed motor- DC servo type

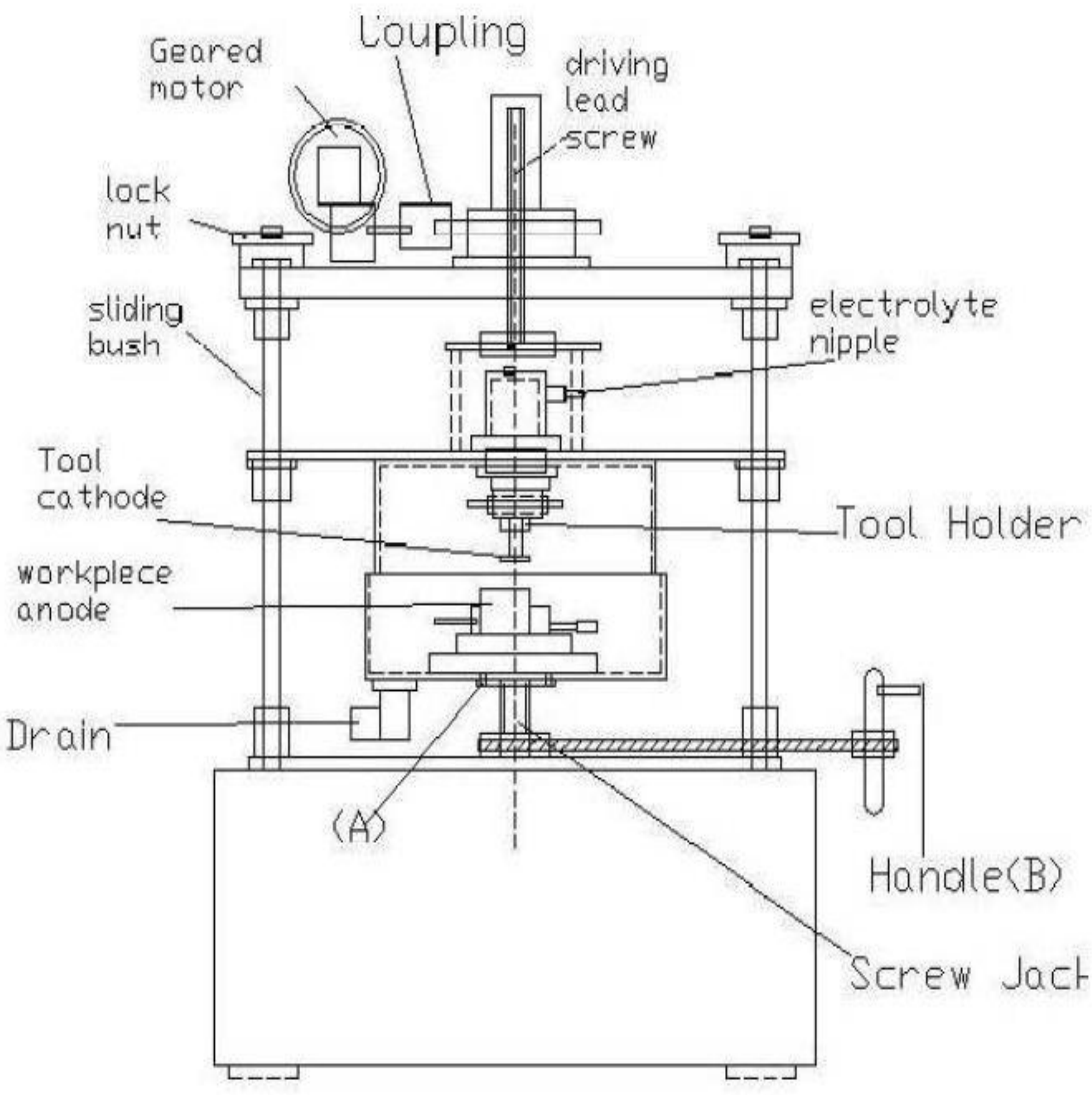


Fig.3.1 Schematic diagram of ECM

Fig. 3.2 ECM Set Up

3.1.2 Control Panel

Through control panel we adjust the current (I), voltage (V), feed rate (F) and time (T) for duration of experiment. The power supply is a perfect integration of, high current electrical, power electronics and precision programmable microcontroller based technologies. Since the machine operates at very low voltage, there are no chances of any electrical shocks during operation.

Technical data

- ✓ Electrical Out Put Rating - 0-300 A. DC at any voltage from 0 - 20 V.
- ✓ Efficiency - Better than 80% at partial & full load condition.
- ✓ Protections - Over load, Short circuit, single phasing.
- ✓ Operation Modes - Manual/Automatic.
- ✓ Timer - 0 - 99.9 min.
- ✓ Tool Feed - 0.2 to 2 mm / min.
- ✓ Z Axis Control - Forward, reverse , auto forward /reverse, through micro controller.

- ✓ Supply - 415 V +/- 10%, 3ϕ AC, 50 Hz.

Fig. 3.3: Control Panel

3.1.3 Electrolyte Circulation system

The electrolyte is pumped from a tank, lined by corrosion resistant coating with the help of corrosion resistant pump & is fed to the job. Spent electrolyte will return to the tank. The hydroxide sludge arising will settle at the bottom of the tank & can be drained out without difficulty. Electrolyte supply shall be governed by flow control valve. Extra electrolyte flow is by passed to the tank. Reservoir provides separate settling and siphoning compartments. All fittings are of corrosion resistant material or of Stainless steel, as required.

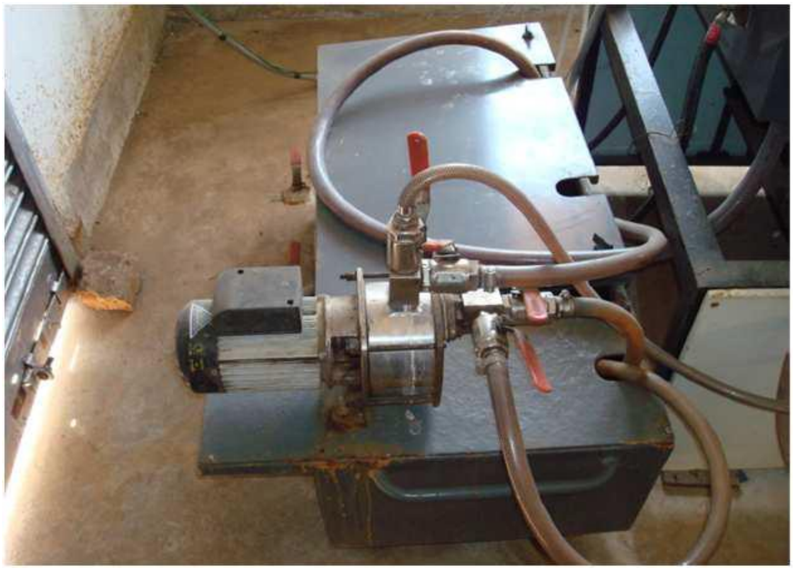


Fig. 3.4: Electrolyte Chamber

3.2 Tool design

In ECM generally tool which is cathode, is made out of non-reacting material such as Copper. So in study of tool design problem in ECM was to determine a cathode shape which will machine a specified work piece shape. In this experiment copper is taken as electrode material as cathode. It is a copper rod of length 55 mm, a through hole is made at the centre by a 4 mm drill bit made up of high speed steel and at one end 10.5 mm diameter groove of length 21 mm is made by a die as shown in fig.

Fig. 3.5 Die

Fig 3.6: tool

Chapter 4
Experimental work

In this chapter experimental work is discussed which consists about formation of the L-9 orthogonal array based on Taguchi design for mild steel, RSM method for mild steel and RSM method for stainless steel (AISI 202) specimen. Orthogonal array reduces the total number of experiments. Total 9 experimental runs have been done for Taguchi design and MRR and SR of the work piece is calculated. Total 20 experimental runs have been done for RSM design and MRR, overcut and circularity error was measured.

4.1 Specifications of work piece materials and the methods used for the experiments

For the first experiment it has been chosen mild steel as work piece. Taguchi design (L_9 orthogonal array) is made for mild steel specimen and work piece is having dimension of length 60 mm, width 45 mm, thickness 5 mm. one piece of mild steel material is taken and experiments are carried out. In the second experiment again mild steel specimen but RSM design is made considering the same factors. In this case work piece is having dimension length 130 mm, width 45 mm, thickness 5 mm whereas for third experiment stainless steel (AISI 202) RSM design is made considering the same factors. In this case work piece dimensions of length 130 mm, width 45 mm, thickness 5 mm. Material removal rate is calculated by taking initial and final weight of work piece before and after the experiment. Overcut and circularity error is analysed by Grey Taguchi coupled with principle component analysis. The surface roughness parameters have been measured using the stylus-type profilometer, Talysurf (Taylor Hobson, Surtronic 3+).

Properties and compositions of the work piece materials is shown below,

Table 4.1: Mild steel properties and composition

Density (gm/cm^3)	7.8
Young's modulus (MPa)	210,000
Carbon content (in percentage)	(0.16 to 0.2)
Other constituents (in percentage)	Mn-1.65, Cu-0.6, Si- 0.6 (fixed compositions) Cr, Co, Nb, Mb, Ti, Ni, W, V, Zr (composition not fixed)
Cost	cheap
Magnetic properties	ferromagnetic
Nature	ductile
Nomial thickness/diameter(mm)	6 to 40
Tensile Strength (kgf/mm^2)	42-54
Percentage Elongation Min.	23

Stainless steel (AISI 202) composition and properties,

Table 4.2: Percentage composition

Sr. No.	**metals**	**percentage**
1.	Carbon	0.12
2.	Manganese	5.5-7.5
3.	Silicone	0.9
4.	Chromium	16-18
5.	Nickel	0.5-4.0
6.	Molybdenum	0.2
7.	Phosphorus	0.06
8.	Nitrogen	0.2

Table 4.3: Properties

Density (gm/cm^3)	7.9
Specific Heat (Kj/kgk)	0.5
Thermal Conductivity (W/m°C) 20°C	16.3-18.4
Abrasion Resistance	Good
Cold Forming	Good
Weldability	Good
Scaling Temperature (K)	800
Structure	Austenitic
Young's modulus (MPa)	195,000
Thermal expansion (x 10^{-6}/°C)(200-600°C)	17-19
Heat capacity (J/kg°C)	20°C
Resistivity (nΩm) 20°C	850
Ferromagnetism	No

4.2 Taguchi design

Taguchi's philosophy was developed by Dr. Genichi Taguchi and is an effective tool for the design of high quality manufacturing system. Taguchi's Orthogonal Array (OA) provides a set of experiments with less number of experimental runs, and Taguchi's signal-to-noise ratios (S/N), which are logarithmic functions of desired output; assist as objective functions in the optimization process. Taguchi technique uses a statistical measure of performance called signal-to noise ratio. The S/N ratio takes both the mean and the variability into account. The S/N ratio is the ratio of the mean (Signal) to the standard deviation (Noise). The ratio depends on the quality characteristics of the product/process to be optimized. The standard S/N ratios generally used are

Nominal is Best (NB), lower the better (LB) and Higher-the-Better (HB). Once experimental data (quality attribute value) is normalized using NB/LB/HB criteria; normalized value lies in between zero to one. Zero represents worst quality to be rejected and one represents most satisfactory quality. Since S/N ratio is expressed as mean (signal) to the noise (deviation from the target); maximizing S/N ratio certifies minimum deviation and hence it is (S/N ratio) to be maximized. Taguchi method attempts to minimize the noise because the elimination of noise factor is not viable. Taguchi method offers much compact variance for the experiment with optimum setting of process control parameters. That's why Taguchi methods are use in design of experiment with parametric optimization processes to get the desired results.

4.3 Taguchi design in Minitab:

MINITAB offers both static and dynamic response tests in a static response tests; the quality characteristic of interest has a fixed level. In a dynamic response tests, the quality characteristic operates over a range of values and the goal is to improve the relationship between an input signal and an output response. MINITAB calculates response tables and generates main effects and interaction plots for:-

- ✓ Signal-to-noise ratios (S/N ratios, which provide a measure of robustness) vs. the control factors.
- ✓ Means (static design) or slopes (dynamic design) vs. the control factors.
- ✓ Standard deviations vs. the control factors.
- ✓ The natural log of the standard deviations vs. the control factors.

A Taguchi design an orthogonal array is the method in which they use different types, two, three, four, five, and mixed level of designs. Features are shown in this table.

Table 4.4: Types of design

Level	2 level design	3 level design	4 level design	5 level design	Mixed level design
Factor	2 to 31 factor	2 to 13 factor	2 to 5 factor	2 to 6 factor	2 to 26 factor

Table 4.5: Machining parameters and their level

Machining parameter	Unit	level		
		Level 1	Level 2	Level 3
Voltage (V)	Volt	8	10	12
Feed rate (F)	mm/min	0.1	0.3	0.5
Concentration(C)	gm/lit	10	12	14

First of all it has been choosing how many factors are available for the experiment. After that in this experiment three factors voltage (V), feed rate (F) and electrolyte concentration(C) has taken into the consideration.

4.5 Response Surface Methodology (RSM): -

Response Surface Methodology (RSM) is a collection of mathematical and statistical techniques for experimental model building. By careful design of experiments, the objective is to optimize a response (output variable) which is affected by several independent variables (input variables). An experiment is a series of tests, called runs, in which changes are made in the input variables in order to identify the reasons for changes in the output response. Equation for response y is given by

$$y = f(x_1, x_2) + e$$

The variables x_1 and x_2 are independent variables where the response y depends on them. The dependent variable y is a function of x_1, x_2, and the experimental error term, denoted as *e*. The error term e represents any measurement error on the response. If the response can be defined by a linear function of independent variables, then the approximating function is a first-order model. A first-order model with 2 independent variables can be expressed as

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \varepsilon$$

If there is a curvature in the response surface, then a higher degree polynomial must be used. The approximating function with 2 variables is called a second-order model:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_{22}^2 + \beta_{12} x_1 x_2 + \varepsilon$$

In each model, the levels of each factor are independent of the levels of other factors. In order to acquire the most effective result in the approximation of polynomials the proper experimental design must be used to collect data. Once the data are collected, the Method of Least Square is used to estimate the parameters in the polynomials. The response surface analysis is performed by using the fitted surface. The response surface designs are types of designs for fitting response surface. Therefore, the objective of studying RSM can be accomplish by

(1) Understanding the topography of the response surface (local maximum, local minimum, ridge lines), and

(2) Finding the region where the optimal response occurs. The goal is to move rapidly and efficiently along a path to get to a maximum or a minimum response so that the response is optimized.

4.6 Grey based Taguchi method

In solving multi objective problems, Taguchi method is coupled with grey relational analysis, because Taguchi alone cannot be capable to solve multi-objective problems. Grey relational analysis is used to adapt a multi-objective problem into a single objective problem and after that Taguchi method is applied. Following are the steps used in Grey based Taguchi method:-

Step.1: - The first step in the grey relational analysis is to normalize the experimental data in the range of 0 to 1.This step is known as grey relational generation. After that Grey relational co-efficient are calculated to represent the relationship between ideal and the actual normalized data. In the normalization three types of data normalization are done:-

1. Lower is the better
2. Higher is the better.
3. Nominal is the best

- Criteria for lower is the better,

$$x_i(k) = \frac{\max\ y_i(k) - y_i(k)}{\max\ y_i(k) - \min\ y_i(k)}$$

- Criteria for higher is the better,

$$x_i(k) = \frac{y_i\ (k) - \min\ y_i(k)}{\max\ y_i(k) - \min\ y_i(k)}$$

- Criteria for nominal is the better,

  Where Xi(k) - Value after the Grey relational generation.

  Min Yi(k) - Smallest value of Yi (k) for Kth Response.

  Max Yi(k) - Maximum value of Yi (k) for Kth Response.

Step 2 .Calculation of Grey relational coefficient

$$\xi_i(k) = \frac{\Delta_{\min} + \psi\Delta_{\max}}{\Delta_{0i}(k) + \psi\Delta_{\max}}$$

Where $\Delta 0i(k) = |X_0(k) - Xi(k)|$ = Difference between absolute values of X0(k) and Xi(k)

Step 3: - After taking average of the Grey relational coefficients, the Grey relational grade can be calculated as:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k)$$

Where n is the number of responses.

4.7 Grey relational analysis coupled with principal component analysis for optimization of parameters

In order to objectively reflect the relative importance for each performance characteristic in grey relational analysis, principal component analysis is used to determine the corresponding weighting values for each performance characteristic. In other words we can say that, principal component analysis is used to determine the corresponding weighting values of each performance characteristics, when this method is coupled with grey relational analysis and used in problem with multiple performance characteristics, will reflect the relative importance for each performance characteristic. The steps used in Grey relational analysis coupled with principal component analysis are as follows:-

Step 1: - The first step is to convert the experimental data into S/N values.

Step 2: - Converted S/N value is normalized.

Step 3: - After S/N value normalization corresponding grey relational coefficients are calculated.

Step 4: - Calculate the grey relational grade using principal component analysis.

Step 5: - Now perform the statistical analysis of variance and get the optimal levels of cutting parameters.

4.8 Procedure of the experiment:

Before starting the experiment the initial weight of the work piece is to be taken to calculate the MRR. After setting all the parameters in the control panel (like feed rate, voltage, current and time) and setting the work piece in the chamber, machining was started by using a copper electrode. In this step work piece is kept in horizontal position, and by using electrode (vertical in position) machining starts from the centre position. Precaution has to be taken such that tip of the electrode should not touch the surface of the work piece. During the whole process the time of machining of the work piece at certain feed rate and voltage is being noted down.

4.9 Observation tables:

Experiment No.1: - Taguchi design (mild steel)

Table 4.6: Observation table

Sr. No.	Voltage (V)	Feed F (mm/min)	Concentration (C)	MRR (mm^3/min)	SR (µm)
1	8	0.1	10	0.0128000	5.3
2	8	0.3	12	0.0355700	7.1
3	8	0.5	14	0.0846000	9.1
4	10	0.1	12	0.0156500	7.2
5	10	0.3	14	0.0406000	8.0
6	10	0.5	10	0.0786000	10.6
7	12	0.1	14	0.0112243	6.6
8	12	0.3	10	0.0222400	10.2
9	12	0.5	12	0.0519180	11.3

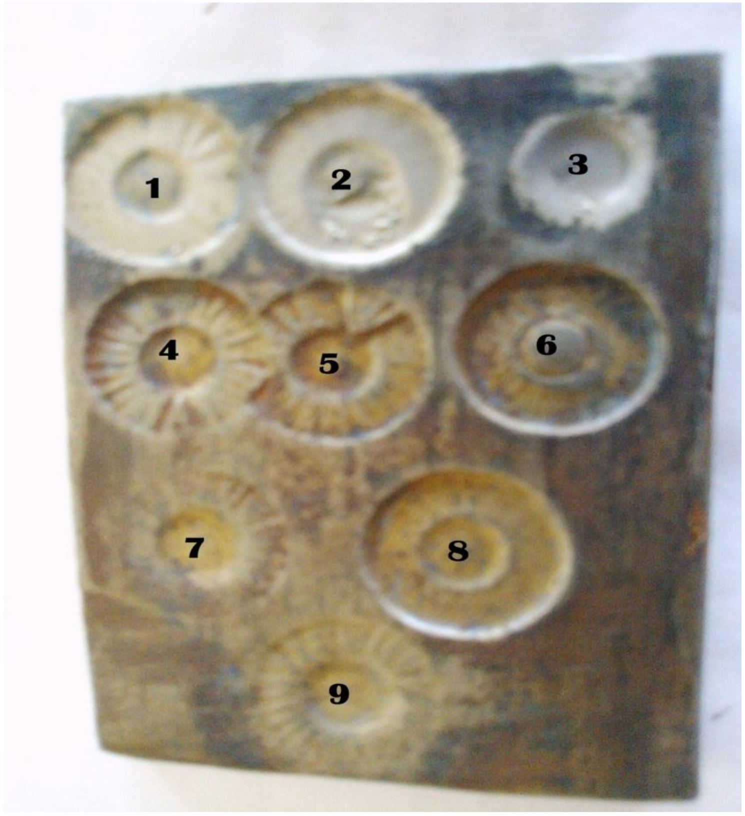
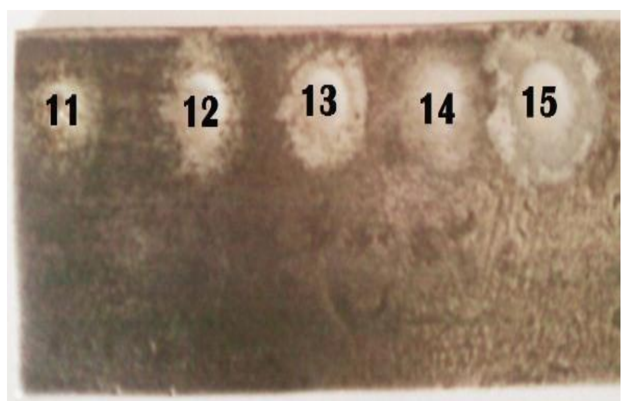


Fig. 4.1 Work piece after machining.

Experiment No. 2: - RSM Design (mild steel)

Table 4.7: Observation table

Std Order	Run Order	Pt Type	Blocks	Voltage (V)	Feed F (mm/min)	Concentration (C)	MRR (mm^3/min)	SR (µm)
6	1	0	1	10.000	0.2000	12.000	0.0072820	7.0
5	2	0	1	10.000	0.2000	12.000	0.0063282	5.0
4	3	1	1	8.000	0.3000	14.000	0.0322564	9.8
2	4	1	1	12.000	0.3000	10.000	0.0044103	6.4
1	5	1	1	8.000	0.1000	10.000	0.0021794	12.0
3	6	1	1	12.000	0.1000	14.000	0.0060513	7.0
12	7	0	2	10.000	0.2000	12.000	0.0071820	5.0
10	8	1	2	12.000	0.3000	14.000	0.0256920	6.6
11	9	0	2	10.000	0.2000	12.000	0.0072820	5.0
7	10	1	2	12.000	0.1000	10.000	0.0030512	8.6
8	11	1	2	8.000	0.3000	10.000	0.0128700	4.4
9	12	1	2	8.000	0.1000	14.000	0.0102820	10.8
18	13	-1	3	10.000	0.2000	15.266	0.0306923	7.6
20	14	0	3	10.000	0.2000	12.000	0.0072820	5.0
17	15	-1	3	10.000	0.2000	8.734	0.0024871	6.6
16	16	-1	3	10.000	0.3633	12.000	0.0199487	4.8
14	17	-1	3	13.266	0.2000	12.000	0.0238460	6.8
13	18	-1	3	6.734	0.2000	12.000	0.0160000	8.2
15	19	-1	3	10.000	0.0367	12.000	0.0036667	7.2
19	20	0	3	10.000	0.2000	12.000	0.0172820	5.0



. Fig. 4.2: Work piece after machining

Experiment No. 3: - RSM Design (Stainless steel AISI 202)

Table 4.8: Observation table

Std Order	Run Order	Pt Type	Blocks	Voltage (V)	Feed F (mm/min)	Concentration (C)	MRR (mm^3/min)
6	1	0	1	10.000	0.2000	12.000	0.034230
5	2	0	1	10.000	0.2000	12.000	0.029520
4	3	1	1	8.000	0.3000	14.000	0.033550
2	4	1	1	12.000	0.3000	10.000	0.059870
1	5	1	1	8.000	0.1000	10.000	0.013871
3	6	1	1	12.000	0.1000	14.000	0.015435
12	7	0	2	10.000	0.2000	12.000	0.034446
10	8	1	2	12.000	0.3000	14.000	0.047769
11	9	0	2	10.000	0.2000	12.000	0.027487
7	10	1	2	12.000	0.1000	10.000	0.015650
8	11	1	2	8.000	0.3000	10.000	0.026330
9	12	1	2	8.000	0.1000	14.000	0.011500
18	13	-1	3	10.000	0.2000	15.266	0.014307
20	14	0	3	10.000	0.2000	12.000	0.027615
17	15	-1	3	10.000	0.2000	8.734	0.016884
16	16	-1	3	10.000	0.3633	12.000	0.068089
14	17	-1	3	13.266	0.2000	12.000	0.028530
13	18	-1	3	6.734	0.2000	12.000	0.011833
15	19	-1	3	10.000	0.0367	12.000	0.011179
19	20	0	3	10.000	0.2000	12.000	0.025390

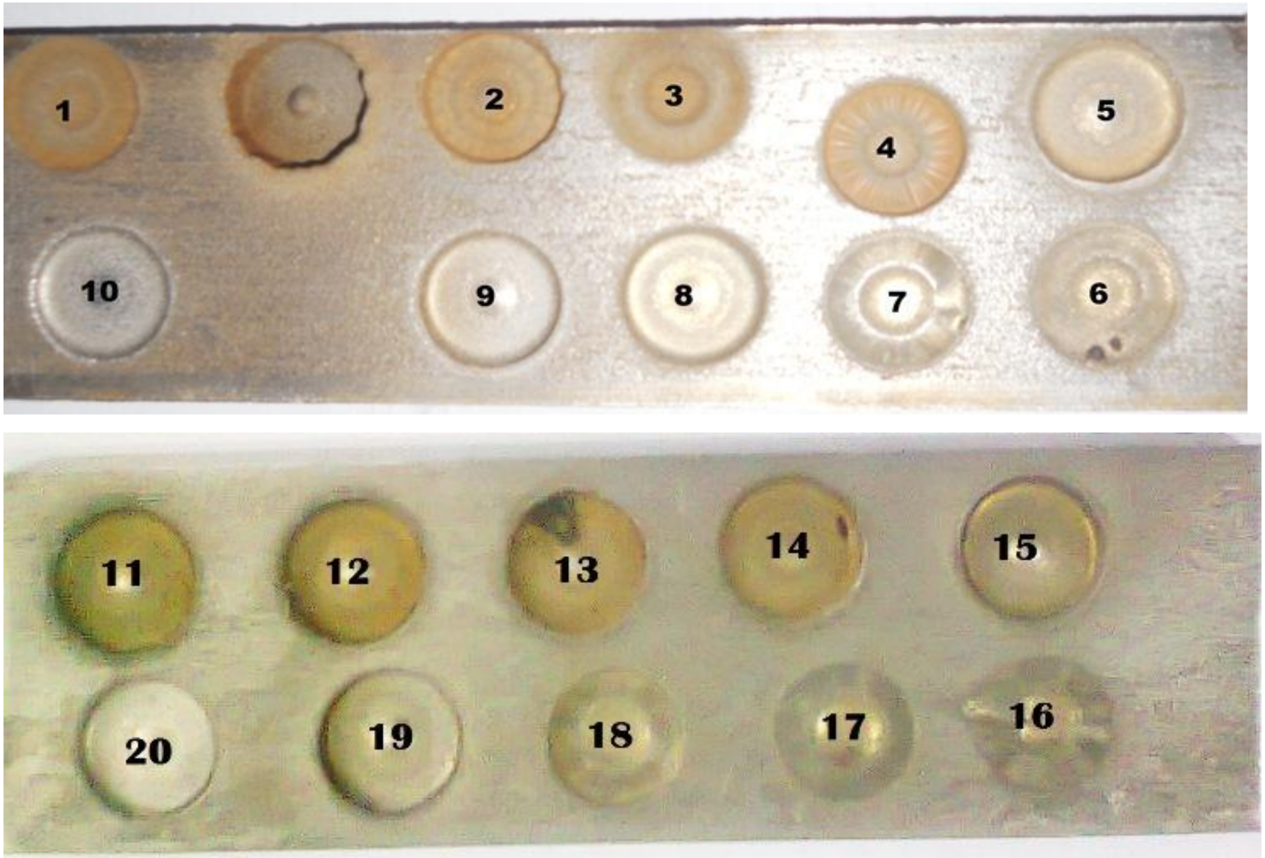


Fig. 4.3: Work piece after machining.

Table 4.9: Experimental data related to Overcut and Circularity (L_9 Orthogonal array design)

Sr. No.	Voltage (V)	Feed F (mm/min)	Concentration (C)	Circularity error	Overcut (mm)
1.	8	0.1	10	0.352	1.1900
2.	8	0.3	12	0.179	1.0925
3.	8	0.5	14	0.056	1.2390
4.	10	0.1	12	0.181	0.8805
5.	10	0.3	14	0.104	0.9105
6.	10	0.5	10	0.073	1.1775
7.	12	0.1	14	0.081	1.2315
8.	12	0.3	10	0.090	1.2415
9.	12	0.5	12	0.191	1.2400

Table 4.10: Data preprocessing of each performance characteristics (Normalization of experimental data)

Sr. no.	Voltage (V)	Feed F (mm/min)	Concentration (C)	Normalisation 1 (Circularity Error)	Normalisation 2 (Overcut)
1.	8	0.1	10	0.00000	0.14266
2.	8	0.3	12	0.58446	0.41274
3.	8	0.5	14	1.00000	0.00693
4.	10	0.1	12	0.57770	1.00000
5.	10	0.3	14	0.83784	0.91690
6.	10	0.5	10	0.94257	0.17729
7.	12	0.1	14	0.91554	0.02770
8.	12	0.3	10	0.88514	0.00000
9.	12	0.5	12	0.54392	0.00416

Table 4.11: Principal component analysis for L9 OA experimental observations

Sr. No.	Grey coefficient 1	Grey coefficient 2	overall grey grade	PC1 (Ψ_1)	PC2 (Ψ_2)	PC1square (Ψ_1^2)	PC2 square (Ψ_2^2)
1.	0.33333	0.36837	0.350850	-0.140312	-0.025771	0.019688	0.000664
2.	0.54613	0.45987	0.502999	-0.300373	-0.649404	0.090224	0.421725
3.	1.00000	0.33488	0.667440	0.173834	-0.984799	0.030218	0.969830
4.	0.54212	1.00000	0.771062	-0.879189	-0.748843	0.772974	0.560766
5.	0.75510	0.85748	0.806292	-0.750462	-0.989687	0.563193	0.979480
6.	0.89697	0.37801	0.637490	-0.004099	-0.959086	0.000017	0.919847
7.	0.85549	0.33960	0.597548	0.138143	-0.905482	0.019083	0.819898
8.	0.81319	0.33333	0.573260	0.159895	-0.870573	0.025566	0.757898
9.	0.52297	0.33426	0.428614	0.094169	-0.535721	0.008868	0.286997

Table 4.12: (Analysis of covariance matrix) eigenvalues, accountability proportion (AP) and cumulative accountability proportion (CAP) computed for the two major quality indicators, Eigen analysis of the Covariance Matrix

Eigenvalue	0.15963	0.09685
Proportion	0.622	0.378
Cumulative	0.622	1.000

Variable	PC1(Ψ_1)	PC2(Ψ_2)
normalisation 1	0.181	-0.984
normalisation 2	-0.984	-0.181

Table 4.13: Calculation of composite principal component (overall quality index) and corresponding S/N ratios

Sr.No.	Eigen vector	composite principal component	S/N Ratio composite
1.	0.44400	0.14266	16.9140
2.	1.15922	0.71551	2.9077
3.	1.78122	1.00002	-0.0002
4.	1.66330	1.15488	-1.2507
5.	0.81139	1.24204	-1.8827
6.	0.92994	0.95910	0.3628
7.	0.91931	0.91596	0.7625
8.	0.92980	0.88514	1.0598
9.	0.44400	0.54393	5.2891

4.10: Calculation

MRR is calculated by the following formula:-

$$\text{MRR} = \frac{(W_0 - W_1) \times 10^{-3} \times 10^{9}}{\rho_w \times \ time} \, {mm^3}/{min}$$

MRR = Material removal rate

W_0 = initial weight

W_1 = final weight

ρ_w = density of the workpiece

Overcut is measured by the following formula:-

$$\text{Overcut} = \frac{\text{outer diameter} - \text{actual diameter}}{2} = \frac{\text{outer diameter} - 12.5}{2}$$

Circularity error = Maximum diameter - Minimum diameter

Chapter 5

Results and discussions

In this chapter, the responses such as MRR, SR, overcut and circularity error are calculated from the observation tables, which are analyses and discussed.

5.1 Experimental analysis and discussions:

Experiment No.1 (Taguchi design for Mild steel)

5.1.1 Effect on MRR: - The machinability of ECM depends on the feed rate, voltage and electrolyte concentration. The influence of various machining parameters on MRR (means) are shown in fig. 5.1. The MRR is slightly increases with increase in feed rate after that feed rate have enormous effect on MRR and it increases rapidly with increase in feed rate. MRR slightly increases with increase in voltage in the range of 8 to 12 and then decrease, however the effect is less than the feed rate on MRR. But MRR slightly decreases with increases in concentration then increases with increase in concentration.

Table-5.1 Analysis of Variance for Means of MRR

Source	DF	Seq SS	Adj SS	Adj MS	F	P
V	2	0.000524	0.000524	0.000262	6.68	0.130
F	2	0.005317	0.005317	0.002658	67.74	0.015
C	2	0.000193	0.000193	0.000097	2.46	0.289
Residual Error	2	0.000078	0.000078	0.000039		
Total	8	0.006112				

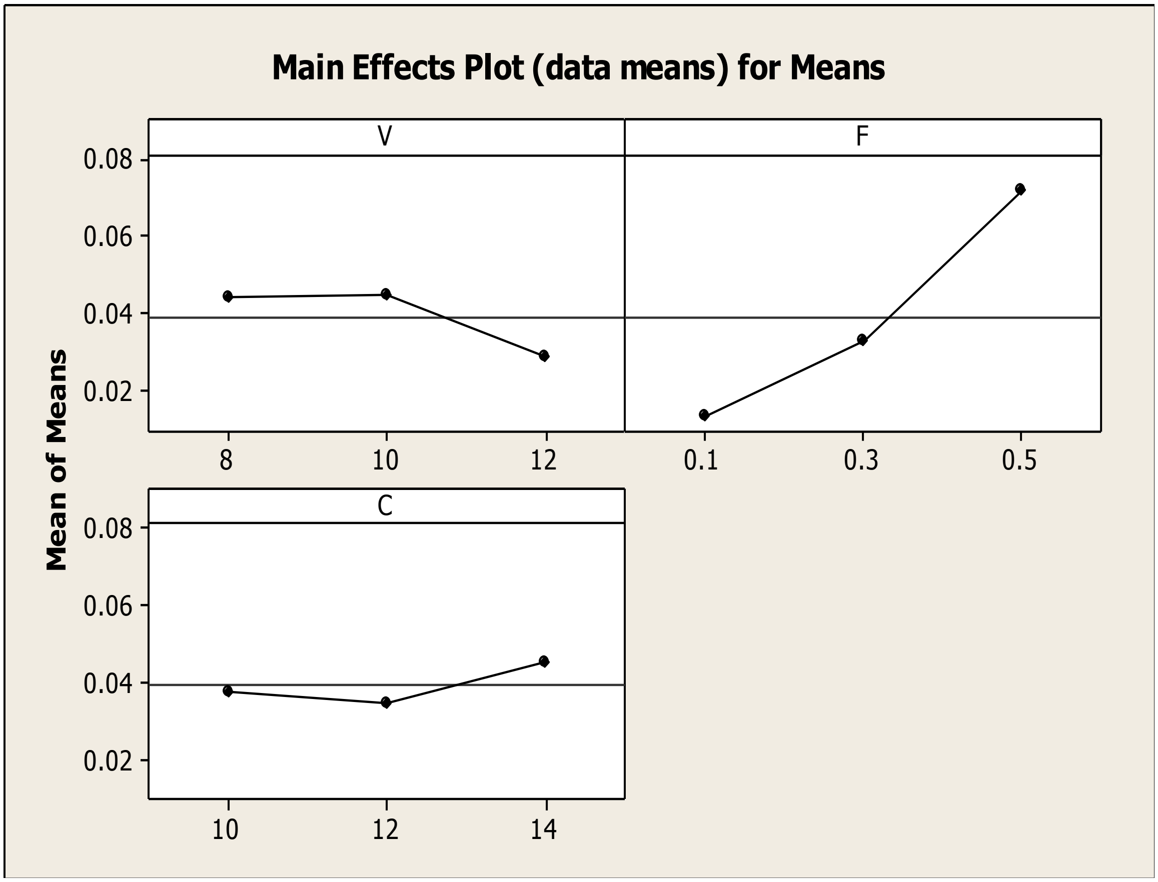


Fig.5.1 Main effects of machining parameters on MRR (data means)

Table-5.2 Taguchi analysis response table for MRR: larger is better

Level	V	F	C
1	0.04432	0.01322	0.03788
2	0.04495	0.03280	0.03438
3	0.02846	0.07171	0.04547
Delta	0.01649	0.05848	0.01110
Rank	2	1	3

In Table 5.2, the main effects of feed, voltage and concentration of electrolyte are 0.05848, 0.01649 and 0.01110 respectively, on MRR in mm^3/min, in order of significance. In which there feed rate is important factor and then voltage and the last electrolyte concentration.

The Estimated Model Coefficients for Means of MRR is shown in Table 5.3. The parameter R^2 defines the amount of variation observed in MRR is explained by the input factors. R^2 = 98.7 % indicates that the model is able to predict the response with high accuracy. Adjusted R^2 is a modified R^2 that has been adjusted for the number of terms in the model. If needless terms are included in the model, R^2 can be affectedly high, but adjusted R^2 (= 94.9 %.) may get smaller. The standard deviation of errors in the modelling, S= 0.006264, Comparing the p-value to a commonly used α-level = 0.05, it is found that if the p-value is less than or equal to α, it can be concluded that the effect is significant, otherwise it is not significant.

Table-5.3 Estimated Model Coefficients for Means of MRR

Term	Coef	SE Coef	T	P
Constant	0.039245	0.002088	18.794	0.003
V 8	0.005079	0.002953	1.720	0.228
V 10	0.005705	0.002953	1.932	0.193
F 0.1	-0.026020	0.002953	-8.811	0.013
F 0.3	-0.006441	0.002953	-2.181	0.161
C 10	-0.001365	0.002953	-0.462	0.689
C 12	-0.004865	0.002953	-1.648	0.241
S = 0.006264		R^2 = 98.7%		R^2 (adj) = 94.9%

The residual plot of MRR is shown in fig. 5.2. This layout is suitable to define whether the model meets the assumptions of the analysis. Normal probability plot shows that the data are not normally distributed and the variables are influencing the response and standardized residue ranges between -0.008 and 0.004. Residuals versus fitted values indicate the variance is not constant and a nonlinear relationship exists. Histogram proves the data are not normally distributed it may be due to the fact that the number of points are very less. Residuals versus order of the data indicate that there are not systematic effects in the data due to time or data collection order.

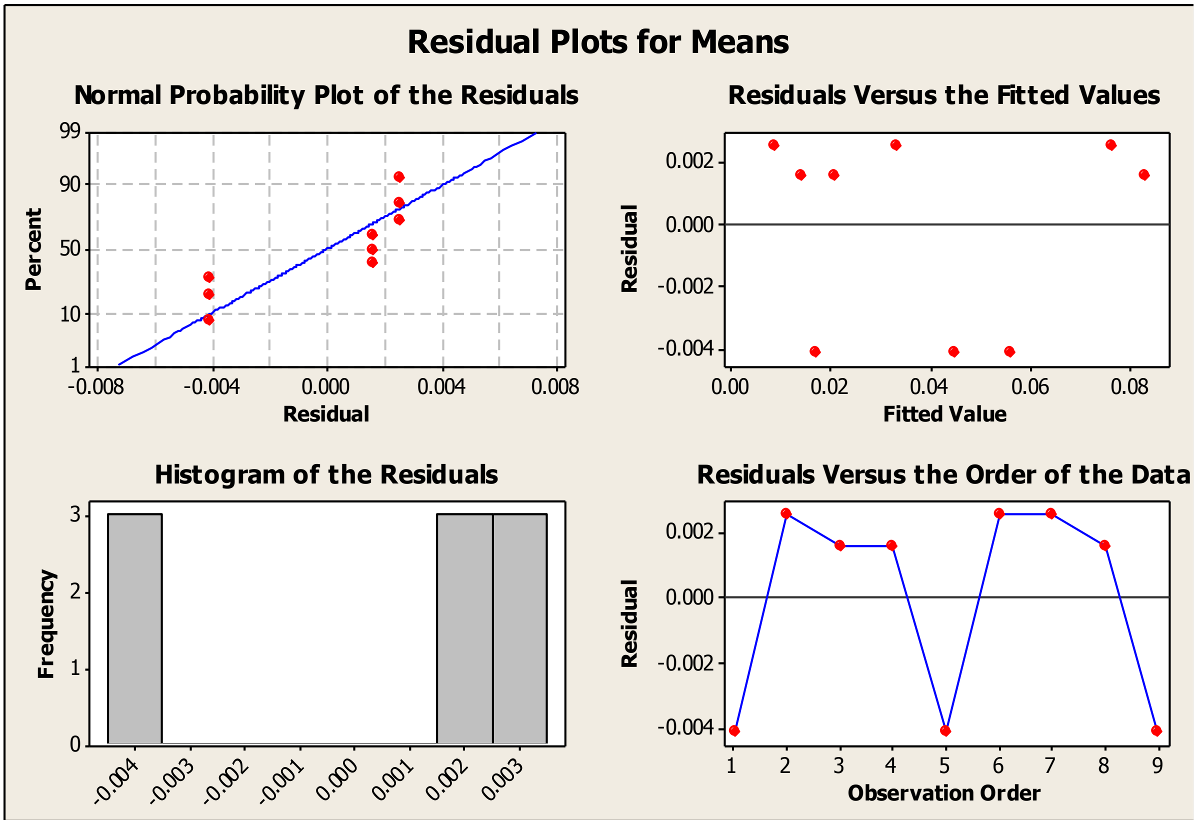


Fig.5.2 Residual Plots for MRR

5.1.2 Effect on SR: - The influence of various machining parameters on SR (means) is shown in fig. 5.1. The SR is slightly increases with increase in feed rate. SR increases with increase in voltage however the effect is less than the feed rate on SR. But SR slightly decreases with increases in concentration.

Table-5.4 Analysis of Variance for Means of SR

Source	DF	Seq SS	Adj SS	Adj MS	F	P
V	2	7.4822	7.4822	3.7411	7.89	0.113
F	2	23.6156	23.6156	11.8078	24.89	0.039
C	2	1.0689	1.0689	0.5344	1.13	0.470
Residual Error	2	0.9489	0.9489	0.4744		
Total	8	33.1156				

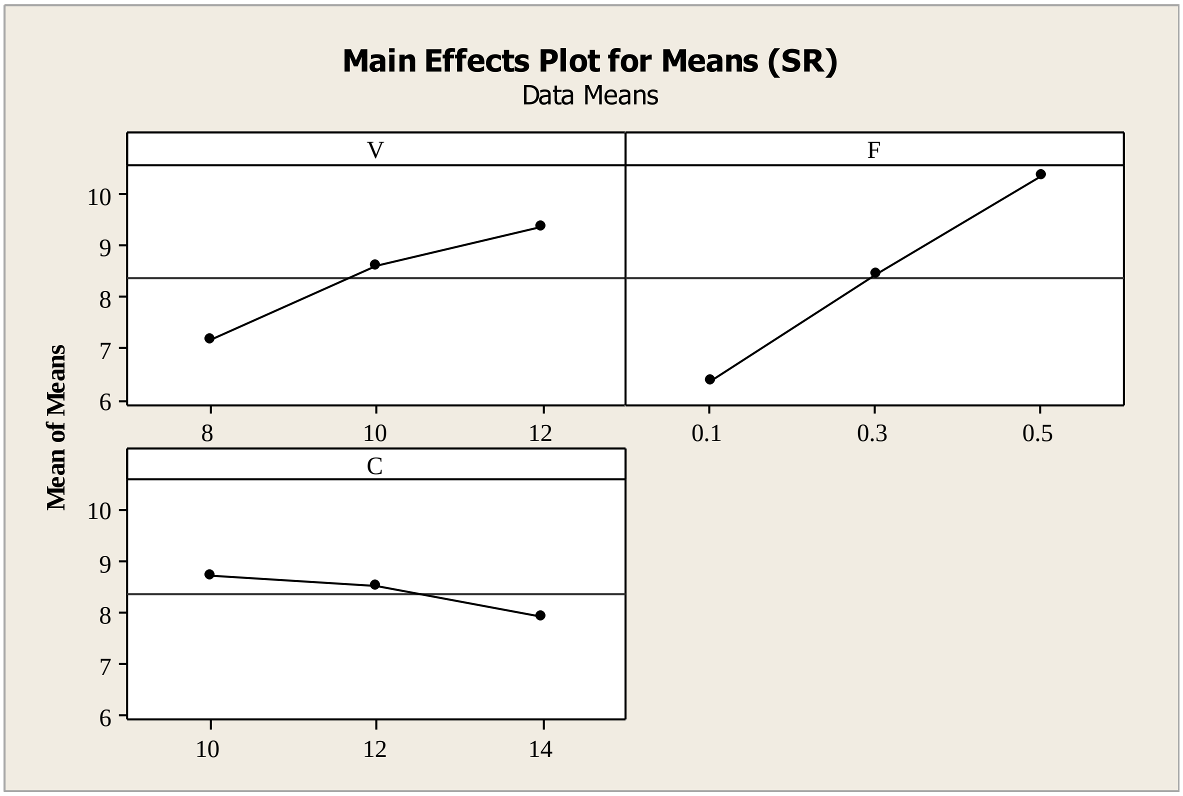


Fig.5.3 Main effects of machining parameters on SR (data means)

Table-5.5 Taguchi analysis response table for SR: smaller is better

Level	V	F	C
1	7.167	6.367	8.700
2	8.600	8.433	8.533
3	9.367	10.333	7.900
Delta	2.200	3.967	0.800
Rank	2	1	3

In Table 5.5, the main effects of feed, voltage and concentration of electrolyte are 3.967, 2.200 and 0.800 respectively, on MRR in mm3/min, in order of significance. In which there feed rate is important factor and then voltage and then electrolyte concentration.

The residual plot for SR is shown in fig 5.4. This residual plot in the graph for normal probability plot indicates the data are not normally distributed and variables are influencing the response. And the Residuals versus fitted value indicate the variation is not constant and no outliers exist. And the Histogram proved the data are not normally distributed it may be due to the fact that the number of points are very less.

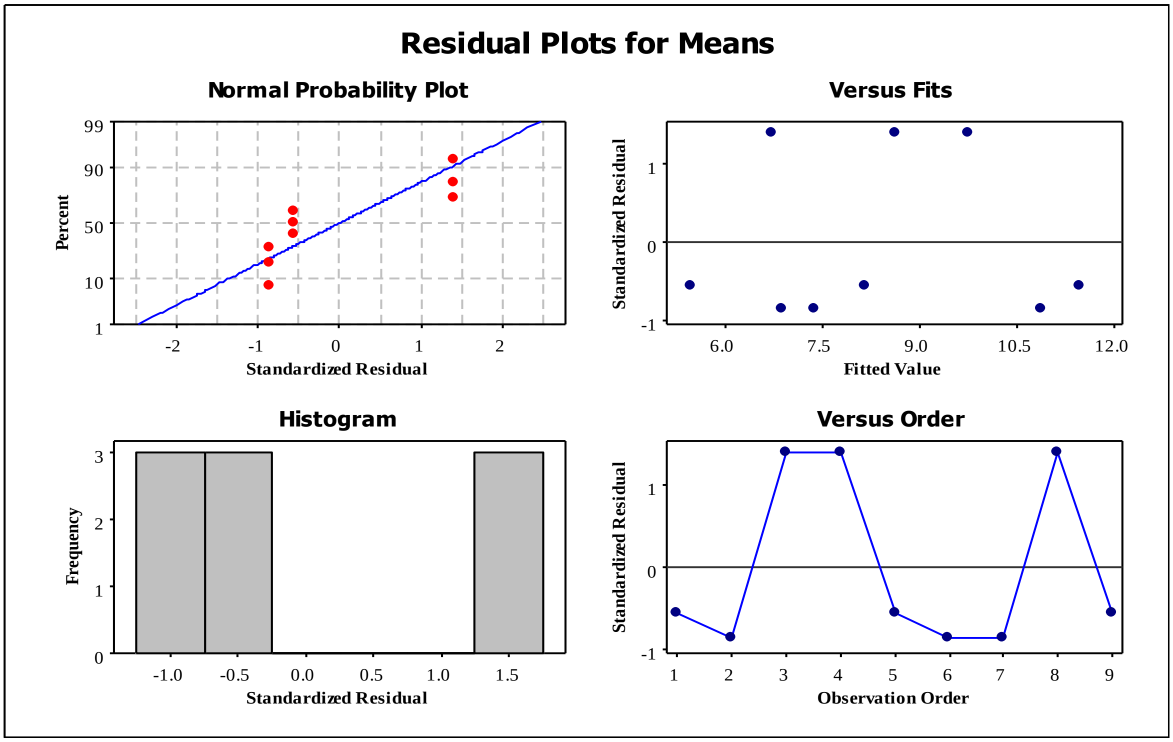


Fig.5.4 Residual Plots for SR

Experiment No.2 (RSM design for Mild steel)

***5.1.3 Effect on MRR:* -** The influence of various machining parameters on MRR (means) are shown in fig. 5.5. The MRR is gradually increases with increase in feed rate. MRR decreases with increase in voltage in the range of 6.734 to 12 and then increases; however the effect is less than the feed rate on MRR. But MRR increases with increases in concentration.

Table 5.6 Analysis of Variance for Means of MRR

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Blocks	2	0.000113	0.000113	0.000057	3.07	0.102
Regression	9	0.001488	0.001488	0.000165	8.98	0.003
Linear	3	0.001203	0.001203	0.000401	21.78	0.000
Square	3	0.000157	0.000157	0.000052	2.84	0.106
Interaction	3	0.000128	0.000128	0.000043	2.31	0.153
Residual Error	8	0.000147	0.000147	0.000018		
Lack-of-Fit	5	0.000097	0.000097	0.000019	1.15	0.484
Pure Error	3	0.000050	0.000050	0.000017		
Total	19	0.001748				

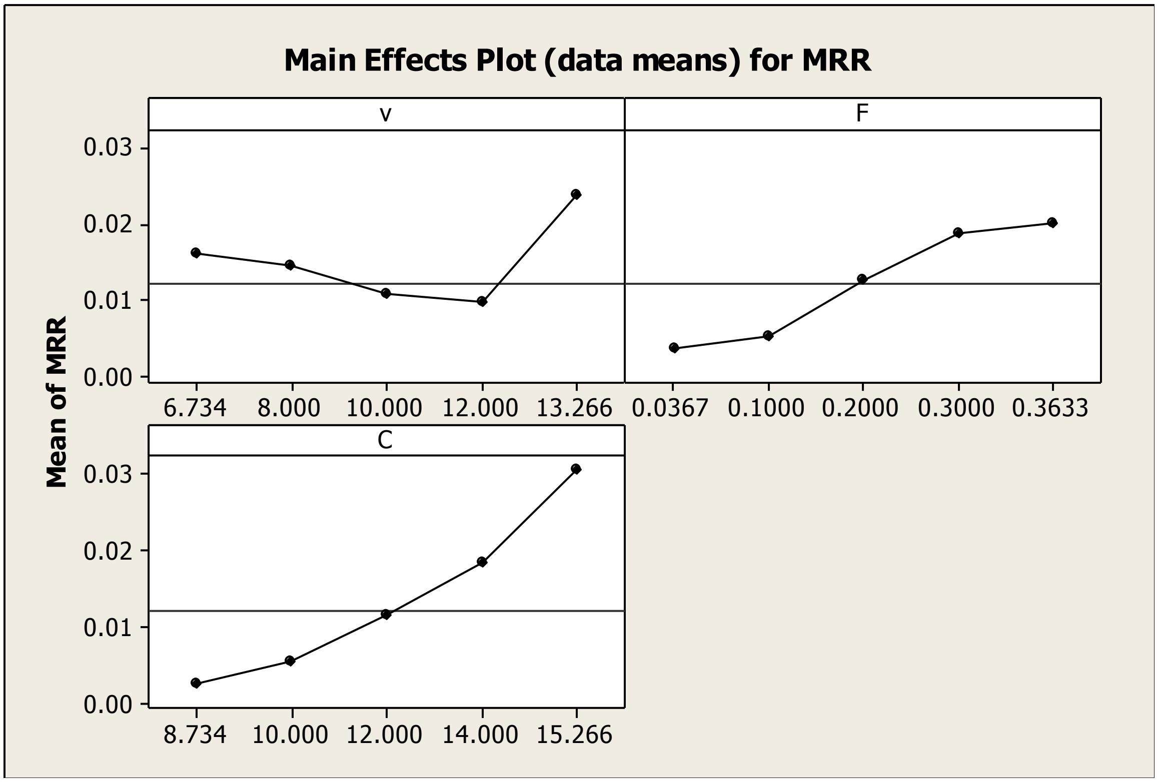


Fig. 5.5 Main effects of machining parameters on MRR (data means)

Table 5.7 Estimated Regression Coefficients for MRR

Term	Coef	SE Coef	T	P
Constant	0.008760	0.001750	5.006	0.001
Block 1	-0.002236	0.001400	-1.597	0.149
Block 2	-0.000927	0.001400	-0.662	0.526
V	-0.000682	0.001919	-0.356	0.731
F	0.009829	0.001919	5.122	0.001
C	0.011982	0.001919	6.244	0.000
V*V	0.008120	0.003149	2.579	0.033
F*F	0.000004	0.003149	0.001	0.999
C*C	0.004786	0.003149	1.520	0.167
V*F	-0.003888	0.004046	-0.961	0.365
V*C	-0.001069	0.004046	-0.264	0.798
F*C	0.009855	0.004046	2.436	0.041
S = 0.004291		R-Sq = 91.6%		R-Sq(adj) = 80.0%

The Estimated Regression Coefficients for MRR is shown in Table 5.7. The parameter R^2 defines the amount of variation observed in MRR is explained by the input factors. R^2 = 91.6 % indicates that the model is able to predict the response with good accuracy. Adjusted R^2 is a modified R^2 that has been adjusted for the number of terms in the model and its value is R^2 (adj) = 80.0%. The standard deviation of errors in the modelling, S= 0.004291, feed (P=0.001) and concentration (P=0.000) is significant and square V*V and F*C interaction is significant while squares like F*F, C*C and V*F, V*C interactions are insignificant.

The residual plot of MRR is shown in fig. 5.6. This layout is suitable to define whether the model meets the assumptions of the analysis. Normal probability plot shows that the data are almost normally distributed and the variables are influencing the response. A standardized residue ranges from -2 and 2. Residuals versus fitted values indicate the variance is constant and a nonlinear relationship exists as well as no outliers exist in the data. Histogram proves the data are almost normally distributed it may be due to the fact that the number of points are very less. Residuals versus order of the data indicate that there are nearly systematic effects in the data due to time or data collection order.

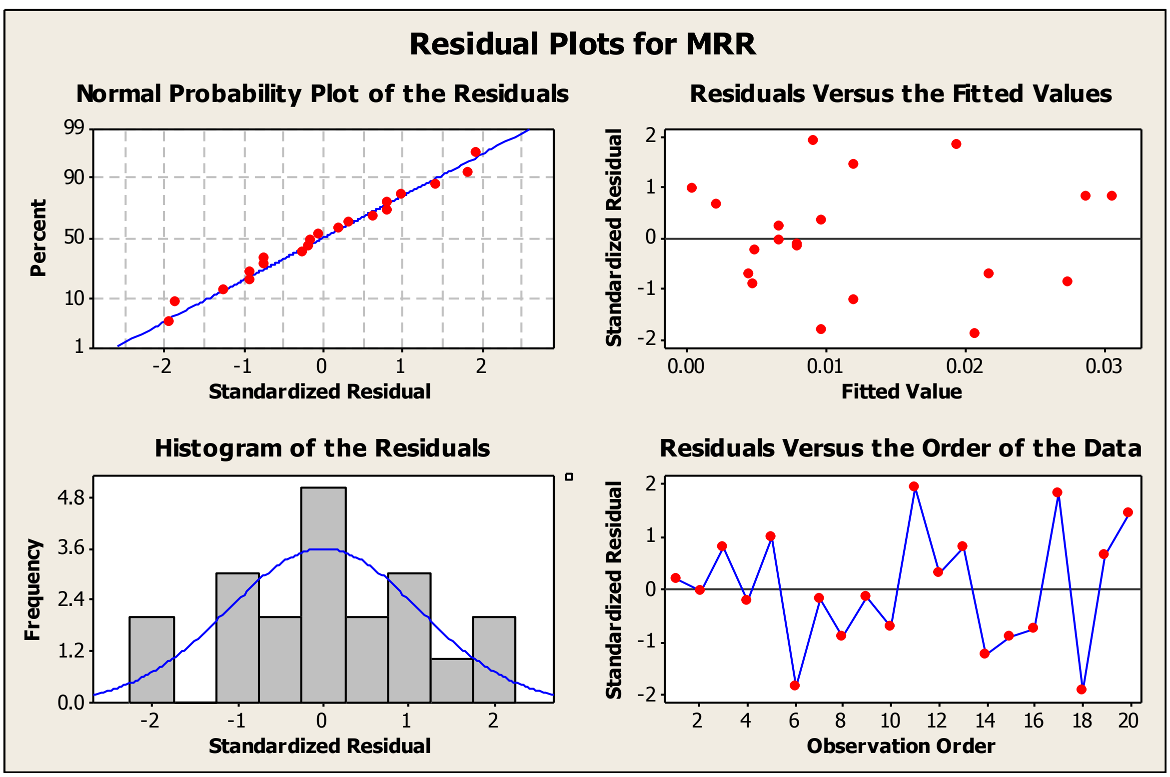


Fig 5.6 Residual Plots for MRR

5.1.4 Effect on SF: - The influence of various machining parameters on SR (means) are shown in fig. 5.7. The SR is initially increases with increase in feed rate then decreases again increases and then decreases. Similar results are obtained in case of other machining parameters like voltage and concentration of electrolyte.

Table 5.8 Analysis of Variance for Means of SR

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Blocks	2	7.741	7.741	3.8707	6.22	0.023
Regression	9	71.207	71.207	7.9119	12.71	0.001
Linear	3	27.183	27.183	9.0609	14.56	0.001
Square	3	26.785	26.785	8.9282	14.34	0.001
Interaction	3	17.240	17.240	5.7467	9.23	0.006
Residual Error	8	4.979	4.979	0.6224		
Lack-of-Fit	5	2.979	2.979	0.5959	0.89	0.576
Pure Error	3	2.000	2.000	0.6667		
Total	19	83.928				

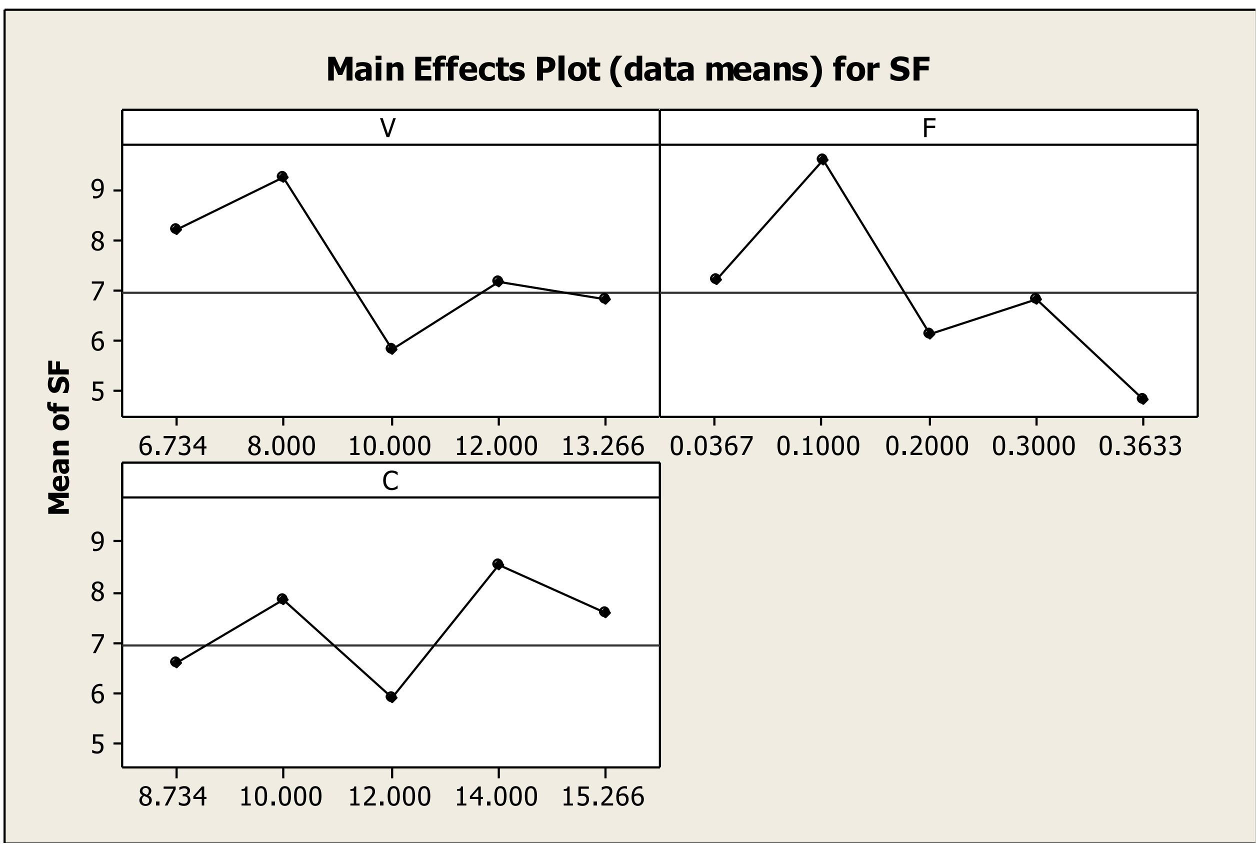


Fig.5.7 Main effects of machining parameters on SR (data means)

Table 5.9: Estimated Regression Coefficients for SR

Term	Coef	SE Coef	T	P
Constant	5.3231	0.3217	16.545	0.000
Block 1	0.8667	0.2574	3.366	0.010
Block 2	-0.2667	0.2574	-1.036	0.331
V	-1.3088	0.3528	-3.709	0.006
F	-1.8517	0.3528	-5.248	0.001
C	0.5429	0.3528	1.539	0.162
V*V	2.8692	0.5789	4.956	0.001
F*F	1.3692	0.5789	2.365	0.046
C*C	2.4692	0.5789	4.265	0.003
V*F	2.0000	0.7438	2.689	0.028
V*C	-1.8667	0.7438	-2.510	0.036
F*C	2.8000	0.7438	3.764	0.006
S = 0.7889	R^2 = 94.1%		R^2 (adj) = 85.9%	

The Estimated Regression Coefficients for SR is shown in Table 5.9. The parameter R^2 defines the amount of variation observed in SR is explained by the input factors. R^2 = 94.1% indicates that the model is able to predict the response with good accuracy. Adjusted R^2 is a modified R^2 that has been adjusted for the number of terms in the model and its value is R^2 (adj) = 85.9%. The standard deviation of errors in the modelling, S= 0.004291, parameters like feed (P=0.001) and voltage (P=0.006) is significant while concentration (C=0.162) is insignificant. Squares V*V, F*F, C*C and interactions V*F, V*C and F*C all are significant.

The residual plot of SR is shown in fig. 5.8. This layout is suitable to define whether the model meets the assumptions of the analysis. Normal probability plot shows that the data are not normally distributed and the variables are influencing the response. A standardized residue ranges from -2 and 2. Residuals versus fitted values indicate the variance is constant and a nonlinear relationship exists as well as no outliers exist in the data. Histogram proves the data are almost normally distributed it may be due to the fact that the number of points are very less. Residuals versus order of the data indicate that there are nearly systematic effects in the data due to time or data collection order.

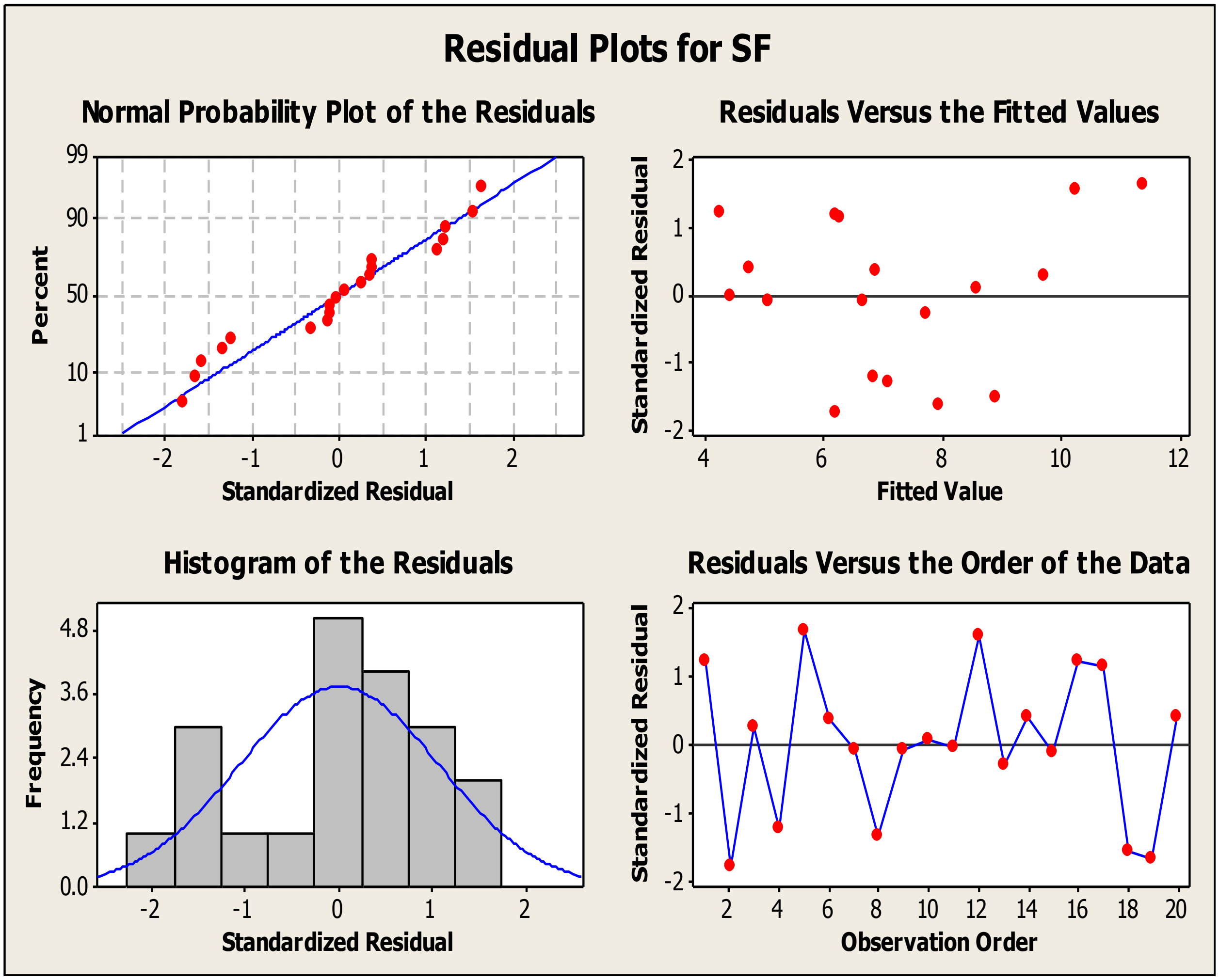


Fig 5.8 Residual Plots for SR

Experiment No.3 (RSM design for Stainless steel AISI 202)

5.1.5 Effects on MRR: - The influence of various machining parameters on MRR is shown in fig. 5.9. The MRR is gradually increases with increase in feed rate while MRR increases with increase in voltage in the range of 6.734 to 12 and then decreases; however the effect is less than the feed rate on MRR. But MRR increases with increases in electrolyte concentration in the range of 8.734 to 12 and then decreases in the range of 12 to 15.266.

Table 5.10: Analysis of Variance for Means of MRR

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Blocks	2	0.000110	0.000110	0.000055	4.29	0.054
Regression	9	0.004561	0.004561	0.000507	39.71	0.000
Linear	3	0.003620	0.003620	0.001207	94.56	0.000
V	1	0.000489	0.000489	0.000489	38.31	0.000
F	1	0.003121	0.003121	0.003121	244.57	0.000
C	1	0.000010	0.000010	0.000010	0.80	0.397
Square	3	0.000683	0.000683	0.000228	17.83	0.001
V*V	1	0.000105	0.000104	0.000104	8.15	0.021
F*F	1	0.000307	0.000266	0.000266	20.85	0.002
C*C	1	0.000270	0.000270	0.000270	21.20	0.002
Interaction	3	0.000258	0.000258	0.000086	6.75	0.014
V*F	1	0.000221	0.000221	0.000221	17.32	0.003
V*C	1	0.000037	0.000037	0.000037	2.89	0.128
F*C	1	0.000001	0.000001	0.000001	0.05	0.826
Residual Error	8	0.000102	0.000102	0.000013		
Lack-of-Fit	5	0.000064	0.000064	0.000013	1.02	0.528
Pure Error	3	0.000038	0.000038	0.000013		
Total	19	0.004773				
S = 0.00357232,		R^2 = 97.86% ,			R^2 (adj) = 94.92%	

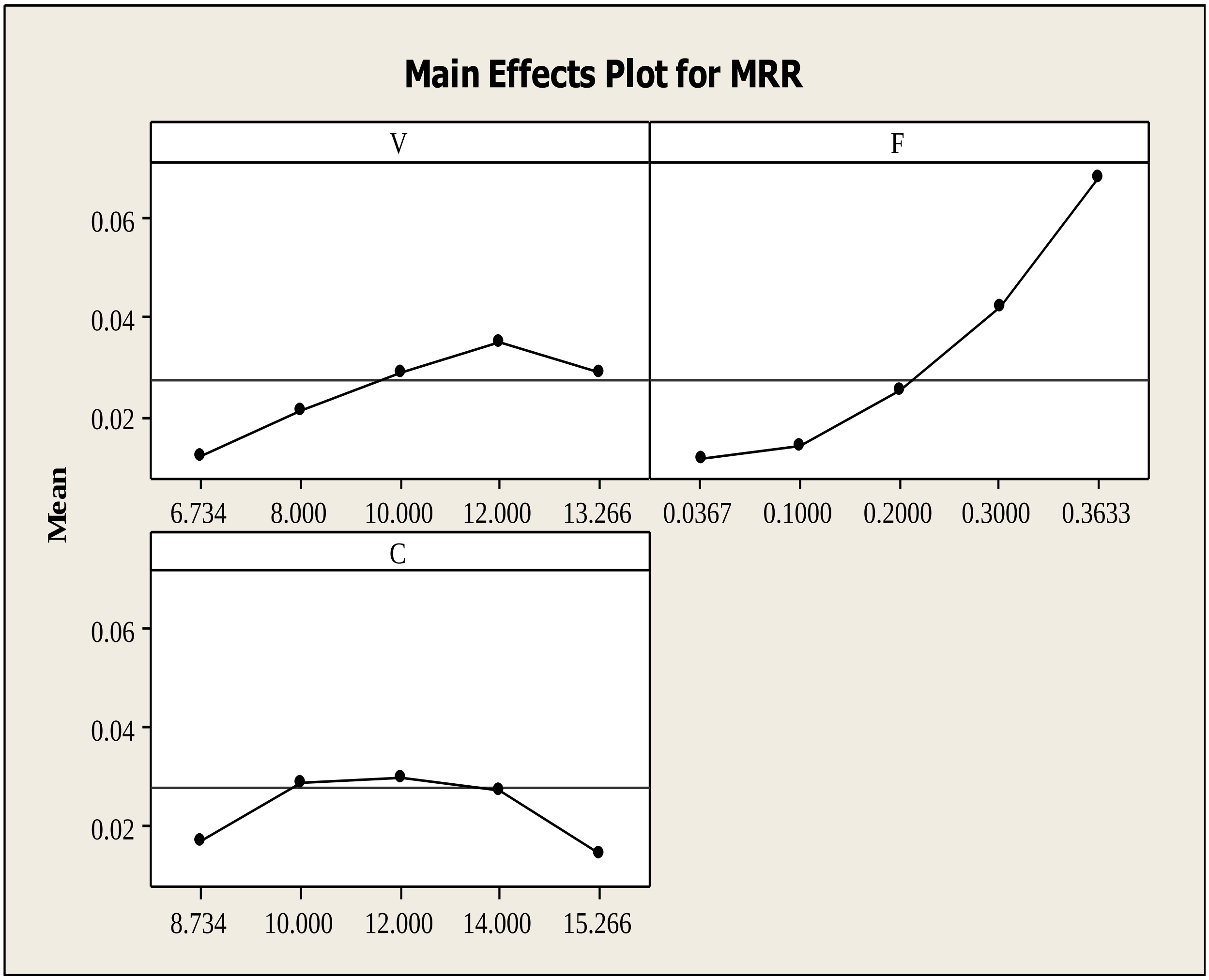


Fig 5.9 Main effects of machining parameters on MRR

The Analysis of Variance for Means of MRR is shown in Table 5.10. The parameter R^2 defines the amount of variation observed in SR is explained by the input factors. R^2 = 97.86%, indicates that the model is able to predict the response with good accuracy. Adjusted R^2 is a modified R^2 that has been adjusted for the number of terms in the model and its value is R^2 (adj) = 94.92%. The standard deviation of errors in the modelling, S=0.00357232 and the parameters like feed (P=0.000) and voltage (P=0.000) is significant and squares like V*V, F*F, C*C all are significant whereas interaction V*F is significant and other interactions are insignificant.

The residual plot of MRR is shown in fig. 5.10. This layout is suitable to define whether the model meets the assumptions of the analysis. Normal probability plot shows that the data are not normally distributed and the variables are influencing the response. A standardized residue ranges from -2 and 2. Residuals versus fitted values indicate the variance is constant and a linear relationship exists as well as no outliers exist in the data. Histogram proves the data are almost normally distributed it may be due to the fact that the number of points are very less. Residuals versus order of the data indicate that somehow systematic effects in the data due to time or collection of data order.

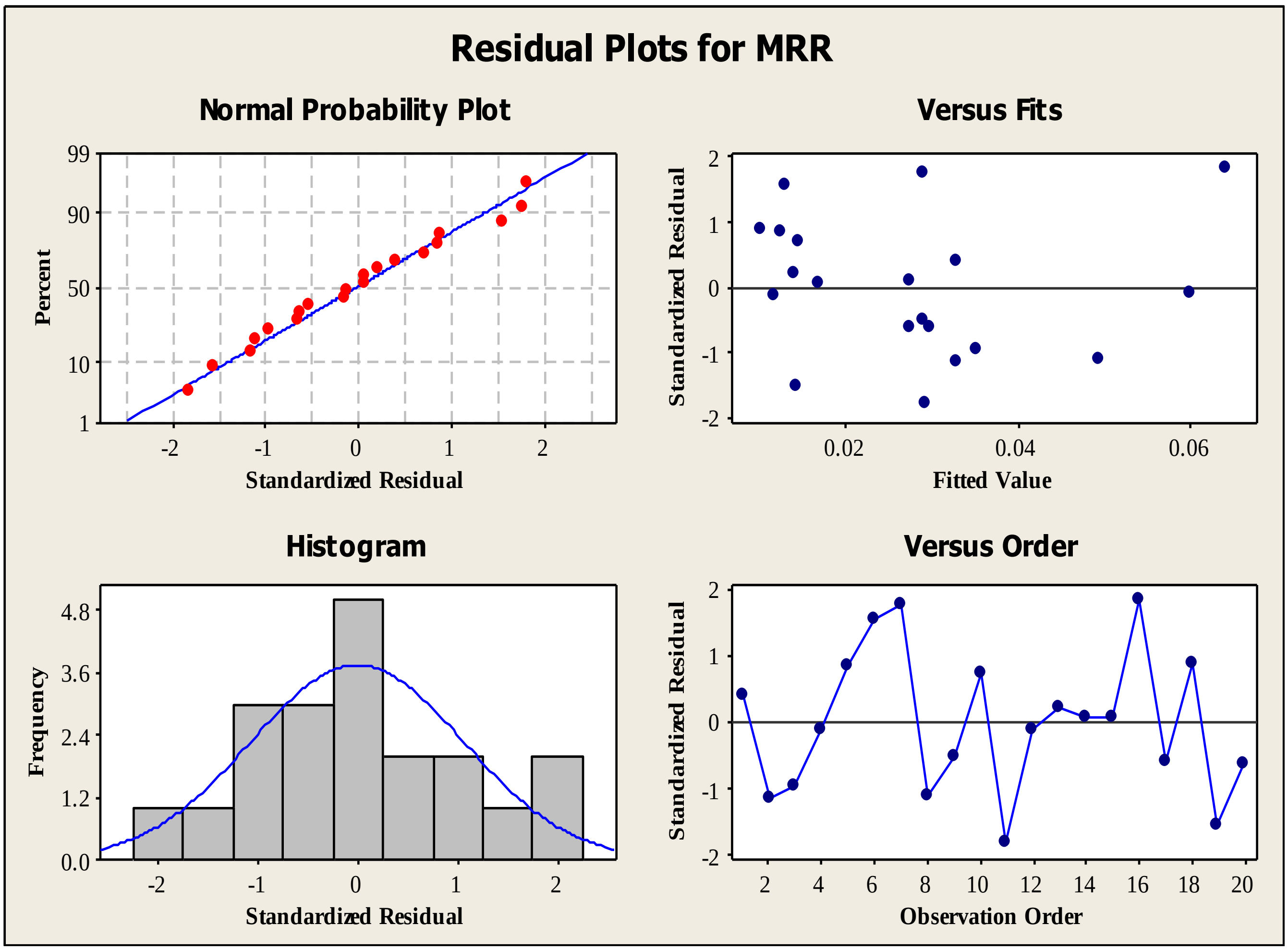


Fig 5.10 Residual Plots for MRR

5.1.6 Effects on Overcut: - The over cut between the dimension of the electrode and the size of the cavity it is natural to the ECM process which is unavoidable however adequate compensation are provided at the tool design. To achieve the accuracy, minimization of over cut is essential. Therefore factors affecting of over cut is essential to recognize. The influence of various machining parameters on Overcut is shown in fig. 5.11. Overcut is decreases up to certain value with increase in feed rate then increases, overcut increases with increase in voltage in the range of 6.734 to 10 and then decreases. But overcut decreases with increases in electrolyte concentration in the range of 8.734 to 14 and then increases.

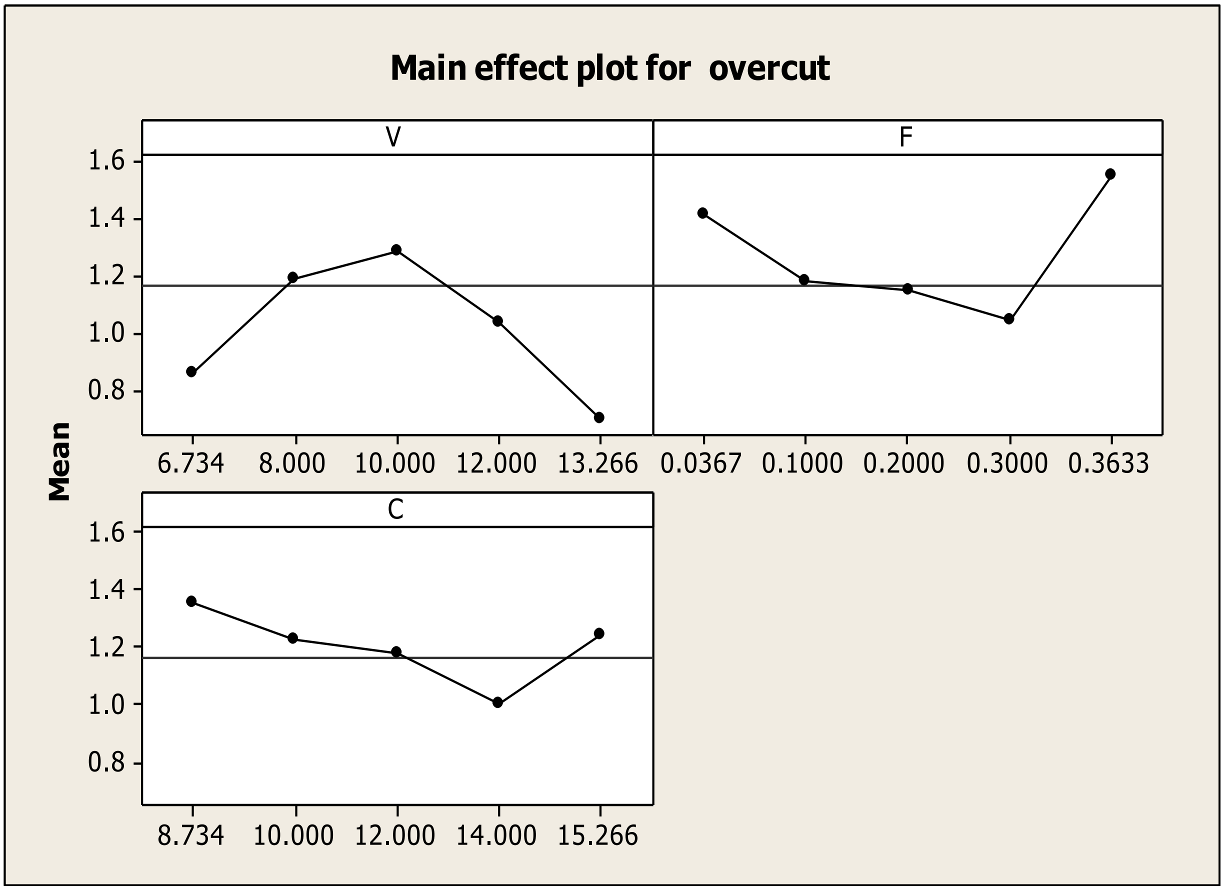


Fig 5.11 Main effect plot for overcut

5.1.7 Effects on circularity error: - The influence of various machining parameters on circularity error is shown in fig. 5.12. circularity error is decreases with increase in feed rate in the range of 0.00367 to 1 and then increases up to 2 then get constant and then increases in the range of 0.3 to 0.366, with increase in voltage circularity error decreases initially in the range of 6.734 to 8 and then increases from 8 to 10 and then decreases from 10 to 12 and then again increases. Circularity error decreases with increases in electrolyte concentration in the range of 8.734 to 10 and then increases in the range of 10 to 12 and then decreases as shown below.

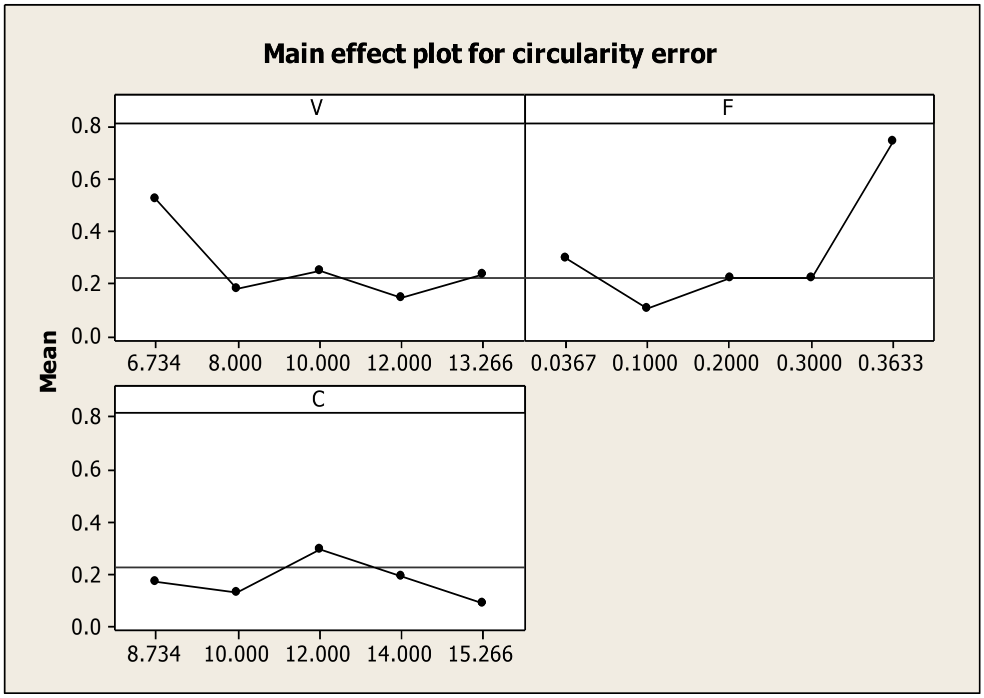


Fig 5.12 main effect plot for circularity error

5.1.8 Effects on overall Grey relational grade: -

Table 5.11: Response table (mean) for overall Grey relational grade

Factors	Grey relational grade				
	Level 1	Level 2	Level 3	Delta	Rank
feed	0.5732	0.6275	0.5778	0.0544	3
Voltage	0.5071	0.7383	0.5331	0.2312	1
concentration	0.5205	0.5676	0.6904	0.1699	2

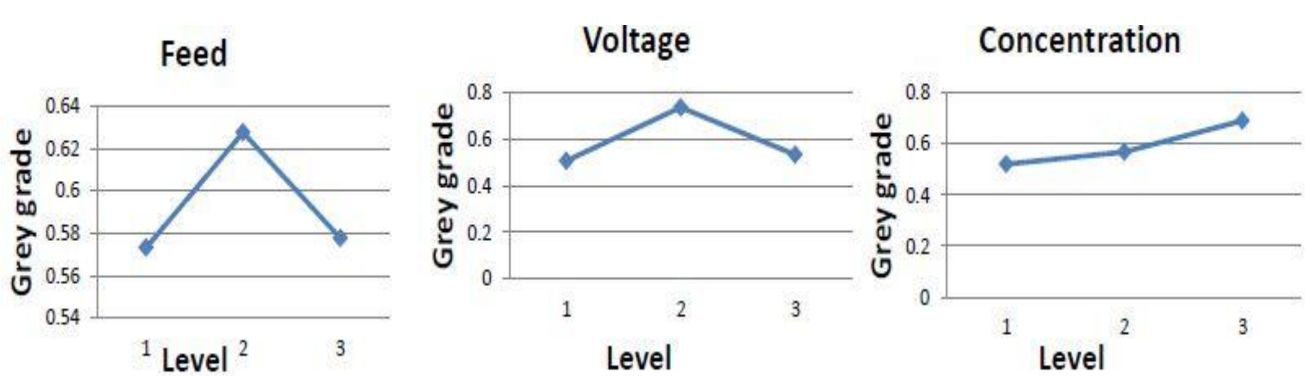


Fig 5.13 S/N ratio plot For Overall Grey Relational Grade

5.1.9 Effects on Composite principle component: --

Table 5.12: Response table (mean) for Composite principle component

Factors	composite principal component				
	Level 1	Level 2	Level 3	Delta	Rank
feed	0.7378	0.9476	0.8344	0.2097	3
Voltage	0.6194	0.7383	0.7817	0.4993	1
concentration	0.6623	0.8048	1.0527	0.3904	2

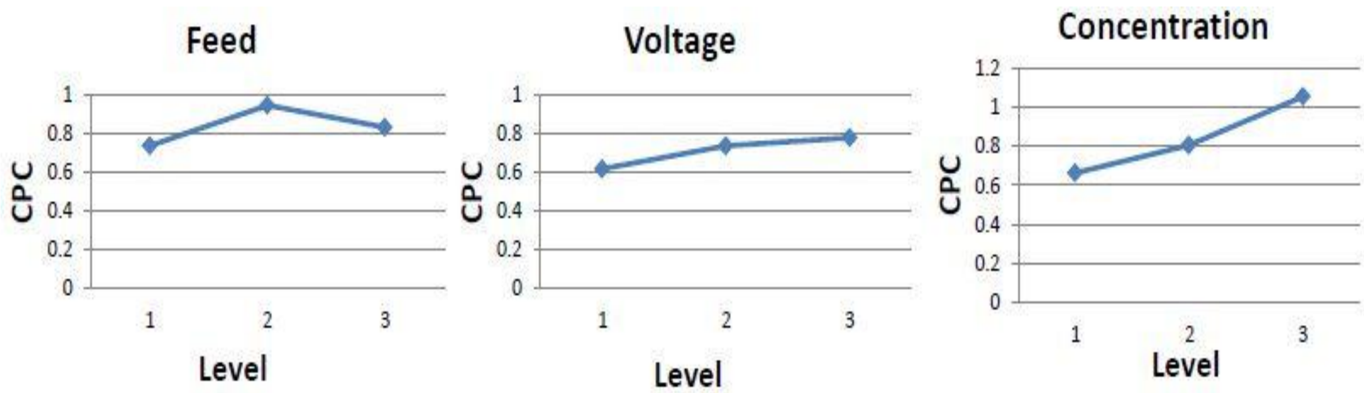


Fig 5.14 S/N ratio plot For Composite principle component

Chapter 6

Conclusions

In the present study on the effect of machining responses are MRR, SR of the mild steel specimen using a Cu electrode (a through hole of 4 mm) tool have been investigated for ECM process. The experiment was conducted under various machining parameters setting of voltage (V), feed (F) and electrolyte concentration(C). L9 OA based on Taguchi design and RSM design was performed by Minitab software results are analysed and theses responses were partially validated experimentally. For stainless steel component machining responses are MRR, SR, Overcut and circularity and Overcut and circularity was analyzed by RSM design and overcut and circularity is also analyzed by Grey Taguchi coupled with PCA.

Concluded on the basis of Taguchi design (first experiment): -

(1) Finding the result of MRR feed is the most influencing factor and then voltage and the last concentration of electrolyte. MRR increased with the increased with the increase in feed. MRR slightly increases with increase in voltage and then decrease. MRR slightly decreases with increases in concentration then increases with increase in concentration

(2) In case of SR feed is the most influencing factor and then voltage and the last concentration of electrolyte. SR increases with increase in feed rate. SR increases with increase in voltage however the effect is less than the feed rate on SR but SR slightly decreases with increases in concentration.

Concluded on the basis of RSM design (second experiment): -

(1) Finding result of MRR concentration is the most influencing factor then feed and the last voltage. MRR is gradually increases with increase in feed rate. MRR decreases with increase in voltage and then increases. MRR increases with increases in concentration.

(2) SR is initially increases with increase in feed rate then decreases again increases and then decreases. Similar results are obtained in case of other machining parameters like voltage and concentration of electrolyte.

Concluded on the basis of RSM design (third experiment): -

(1) Finding the result of MRR feed is the most influencing factor and then voltage and concentration is the least influencing factor. MRR is gradually increases with increase in feed rate. MRR increases with increase in voltage and then decreases; however the effect is less than the feed rate on MRR. MRR increases with increases in electrolyte concentration and after a certain value it decreases.

(2) Overcut is decreases up to certain value with increase in feed rate then increases, overcut increases up to a certain value with increase in voltage and then decreases while it decreases with increases in electrolyte concentration and then increases.

(3) Circularity error decreases with increase in feed rate and then increases and then gets constant for some time and then increases, with increase in voltage circularity error decreases initially and then increases and then decreases and then again increases. Circularity error decreases with increases in electrolyte concentration and then increases up to certain value and then decreases.

(4) For grey relation grade voltage is the most influencing factor then concentration and the last at feed rate. Grey grade increases initially with increase in voltage and then decreases, similarly in case of feed while increases in concentration grey grade increases.

(5) For composite principal component voltage is the most influencing factor then concentration and the last at feed rate. Composite principal component increases with increases in voltage while in case of feed it increases up to certain level then decreases and in case of concentration it increases.

Chapter 7

References

[1] M. G. Fortana , Corrosion Engineering (McGraw-Hill, New York, 1986)

[2] A Moarrefzadeh ,, Finite-Element Simulation of dimensional limitation of Electro Chemical Machining (ECM) Process international journal of multidisciplinary sciences and engineering, vol. 2, no. 7, october 2011

[3] J.A McGeough., Principle of Electrochemical Machining, Chapman & Hall, London, 1974.

[4] K. P. Rajurkr., Electrochemical polishing of biomedical titanium orifice rings, J. Mater. Process. Technol. 35 (1992) 83–91.

[5] O.L. Riggo., C.E. Locke, Anodic Protection, Plenum Press, New York, 1981.

[6]. B. Bhattacharyya, B. Doloi, P.S. Sridhar, Electrochemical micro-machining: new possibilities for micro-manufacturing, J. Mater. Process. Technol. 113 (2001) 301–305.

[7] A. Muttamara and S. Purktong, “Improving the quality of groove in Electro chemical machining(ECM) processed by Taguchi method”, International conference on Mechanical Engineering.20-22Oct.Ubon Ratchathani,2010.

[8] J. Munda, B. Bhattacharya, investigation in to electro-chemical micromachining (EMM) through response surface methodology based approach. International Journal of Advanced Manufacturing Technology (2006).

[9] T. Masuzawa, H.K. Tanshoff, Three dimensional micro machining by machine tools, Annals of CIRP 16 (2) (1997) 621–628.

[10] J. Corbett, P.A. McKeown, G.N. Peggs, R. Whatmore, Nanotechnology: international development and emerging products.

[11] N. Tenigyohi, Current status in, and future trends of, ultraprecision machining and ultrafine material processing, Ann. CIRP 2(2) (1983) 573–582.

[12] M. Dutta, R.V. Shenoy, L.T. Romonkiw, Recent advance in the study of electro-chemical micromachining, J. Eng. Ind. 118 (29) (1996) 29–36.

[13] C. V. Osenbruggen, C. Aeregt, Electrochemical micromachining, Philips Tech. Rev. 42 (1985) 22–31.

[14] Jr. Dolbier., W. R., Beach, W. F., Parylene- AF4: a Polymer with Exceptional Dielectric and Thermal Properties, J. Fluorine Chem, (2003), 122:97-104.

[15] B. Bhattacharyya, S. Mitra, A.K. Boro, Electrochemical machining: new possibilities for micromachining. Robotics and Computer Integrated Manufacturing 18 (2002) 283–289.

[16] Y. M. Leea, S. J. Lee,, C. Y. Lee, D. Y. Chang, The multiphysics analysis of the metallic bipolar plate by the electrochemical micro-machining fabrication process. Journal of Power Sources 193 (2009) 227–232

[17] Y. Lu, R. G. Reddy, Investigation of micro-PEM fuel cell using experimental and modeling methods, Electrochimica Acta 54 (2009) 3952–3959

[18] L. Hotoiu and J. Deconinck Time-efficient simulations of nano-pulsed electrochemical micromachining, The Seventeenth CIRP Conference on Electro Physical and Chemical Machining (ISEM), Procedia CIRP 6 (2013) 470 – 475

[19] M. Datta and D. Harris, Electrochemical micromachining: an environmentally friendly, high speed processing technology, Electrochimica Acta 42 (1997) 3007–3013.

[20] M. Sen, H.S. Shan, A review of electrochemical macro- to micro-hole drilling processes. International Journal of Machine Tools & Manufacture 45 (2005) 137–152.

[21] P. Kumar, B.Tailor, A. Agrawal,S. S. Joshi, Evolution of electrochemical finishing processes through cross innovations and modelling, International Journal of Machine Tools & Manufacture 66 (2013)15–36

[22] M. Datta, L. T. Romankiw, Surface finishing of high-speed print bands II. An electrochemical process for micro-finishing of hardened Fe–13Crstain-less steel, Journal of Electrochemical Society 145(9) (1998) 3052–3057.

[23] P. S. Pa, Design of finish tool in ultrasonic electrochemical finishing process, Materials and Manufacturing Processes 23(2008) 457–462.

[24] R. Mahdavinejad, M. Hatami, On the application of electrochemical machining for inner surface polishing of gun barrel chamber. Journal of materials processing technology 202 (2008) 307–315.

[25] S. J. Lee, Y. M. Lee, M. F. Du, The polishing mechanism of electrochemical mechanical polishing technology. Journal of Materials Processing Technology 140 (2003) 280– 286.

[26] H. hocheng and P.S. Pa, The application of a turning tool as the electrode in electro polishing. Journal of processing technology 120 (2002) 6-12.

[27] T. Dobrev, D. T. Pham and S. S. Dimov, Electro-chemical polishing: a technique for surface improvements after laser milling, Manufacturing Engineering Centre, Cardiff University, Cardiff, CF24 3AA.

[28] T. A. E. Taweel and S. A. Gouda, Study on the wire electrochemical groove turning process, J Appl Electrochem (2011) 41:161–171

[29] P. S. Pa, Design of continuity processes of electrochemical finishing and grinding following turning, Journal of Mechanical Science and Technology 22 (2008) 2197~2202

[30] T. M. A. Maksoud, A.J. Brooks, Electrochemical grinding of ceramic form tooling. Journal of Materials Processing Technology 55 (1995) 70-75.

[31] D.T. Curtis, S.L. Soo, D.K. Aspinwall, C. Sage, Electrochemical super abrasive machining of a nickel-based aeroengine alloy using mounted grinding points. CIRP Annals – Manufacturing Technology 58 (2009) 173–176.

[32] H. Ohmori, K. Katahira, J. Komotori, Y. Akahane, M. Mizutani, T. Naruse, Surface generation of superior hydrophilicity for surgical steels by specific grinding parameters. CIRP Annals - Manufacturing Technology 58 (2009) 503–506.

[33] H. Ohmori, K. Katahira, J. Komotori, M. Mizutani, Functionalization of stainless steel surface through mirror-quality finish grinding. CIRP Annals - Manufacturing Technology 57

(2008) 545–549.

[34] V.V. Lyubimov, A.L. Yerokhin, M.Ya. Tchmir, Mechanisms of synthetic diamond wear in tools for electrochemical grinding. Diamond and Related Materials 7 (1998) 1267–1271.

[35] S. Zaborski, M. Łupak, D. Poro´s. Wear of cathode in abrasive electrochemical grinding of hardly machined materials. Journal of Materials Processing Technology 149 (2004) 414 418.

[36] D. Cliftona, A.R. Mountb, D.J. Jardineb, R. Rothb, Electrochemical machining of gamma titanium aluminide intermetallics. Journal of Materials Processing Technology 108 (2001) 338-348.

[37] D. K. Aspinwal, R. C. Dewes, A. L. Mantle, The Machining of y-TiAl Intermetallic Alloys. CIRP Annals - Manufacturing Technology, Volume 54, Issue 1, 2005, Pages 99-104.

[38] T. Haisch, E. Mittemeijer, J.W. Schultze, Electrochemical machining of the steel 100Cr6 in aqueous NaCl and NaNO3 solutions: microstructure of surface films formed by carbides.Journal of Electrochemical Acta 47 (2001) 235–241.

[39] T. Masuzawa, M. Kimura, Electrochemical Surface Finishing of Tungsten Carbide Alloy. CIRP Annals - Manufacturing Technology, Volume 40, Issue 1, 1991, Pages 199-202.

[40] K.P. Rajurkar, D. Zhu, J.A. McGeough, J. Kozak, A.M.K. De Silva, New Developments in Electrochemical Machining, Annals of the CIRP, 48 (2) (1999), pp. 567–580

[41] N. Bradley (2007), the response surface methodology, Department of Mathematical Sciences Indiana University of South Bend.

[42] B. Bhattacharyya, and J. Munda, Experimental investigation on the influence of electrochemical machining parameters on machining rate and accuracy in micromachining domain, International Journal of Machine Tools & Manufacture 43 (2003) 1301–1310

[43] B Bhattacharyya, J Munda, Experimental investigation into electrochemical micro machining (EMM) process, Journal of Materials Processing Technology 140 (2003) 287–291

[44] A. Prabhakar, (2010) Electrochemical machining of AISI D2 steel with rotary U-shaped tubular copper electrode. M.Tech. Project Report, National Institute of Technology Rourkela, Odhisa, India.

[45] P. N. Rao., (2012), Manufacturing Technology Second Edition, Published by Tata McGraw Hill Education Private Limited, 7 West Patel Nagar, New Delhi, India.

[46] A. Ghosh, and A.K. Mallik, (2010). Manufacturing Science Second Edition, East-West Press Private Limited, New Delhi, India.

[47] P.K. Mishra, (2006), Nonconventional Machining, Narosa Publications, New Delhi, India.

[48] www.google.com

[49] Encyclopedia

[50] www.scopus.com

[51] www.everite.com

[52] scholar google.co.in

[53] www.asminternational.org

[54] linkspringer.com